Good Practice

Guide

—76—

Continuous Steel Reheating Furnaces: Specification, Design and Equipment

BEST PRACTICE PROGRAMME

Energy Efficiency Office

DEPARTMENT OF THE ENVIRONMENT

BEST PRACTICE PROGRAMME

CONTINUOUS STEEL REHEATING FURNACES: SPECIFICATION, DESIGN AND EQUIPMENT

This booklet is No. 76 in the Good Practice Guide Series and it provides an introduction to continuous steel reheating furnaces and the basic principles of combustion technology. Furnace design is reviewed, particularly the aspects which affect energy consumption. An action plan is provided which summarises energy-related aspects of furnace design, and reviews the measures which will help reduce energy consumption.

This is one of two guides dealing with continuous steel reheating furnaces. The other guide is No. 77 in the Good Practice Guide Series and it considers operation and production aspects, maintenance and monitoring with respect to their affect on energy consumption. An action plan is provided which summarises energy-related aspects of operation, and reviews the measures which will help reduce energy consumption. Case histories demonstrating good practice for continuous reheating furnaces are included for reference.

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FOREWORD

This guide is part of a series produced by the Energy Efficiency Office under the Best Practice programme. The aim of the programme is to advance and spread good practice in energy efficiency by providing independent, authoritative advice and information on good energy efficiency practices. Best Practice is a collaborative programme targeted towards energy users and decision makers in industry, the commercial and public sectors, and building sectors including housing. It comprises four inter-related elements identified by colour-coded boxes for easy reference:

— *energy consumption guides*: (blue) energy consumption data to enable users to establish their relative energy efficiency performance;

— *good practice guides and case studies*: (red) independent information on proven energy saving measures and techniques and what they are achieving;

— *new practice projects*: (green) independent monitoring of new energy efficiency measures which do not yet enjoy a wide market;

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ENERGY EFFICIENT OPERATION OF CONTINUOUS STEEL REHEATING FURNACES

1. INTRODUCTION

The iron and steel industry consumes about 5.4% of the total energy used each year in the UK. Continuous steel reheating furnaces use approximately 36 PJ (340 million therms) of liquid and gaseous fuels (54% natural gas, 36% other gaseous fuels and 10% fuel oils) per year to reheat approximately 17 million tonnes of steel. Fuel costs exceed £80 million/year.

All qualities of steel from stainless grades to alloy and carbon steels may be reheated. Continuous steel reheating furnaces generally serve one of two types of rolling mill:

- Primary mills which are mainly used to reheat cast steel ingots, blooms or continuously cast blooms for the production of billets, slabs or semi-finished products. Although these products can be used directly, they are usually the feedstock for secondary rolling mills;
- Secondary mills which produce strip, plate, bar, rod, rails and sections. In many steelworks, these are the finished saleable products, although they may undergo further processing by their purchasers to produce engineering components, domestic appliances and other finished steel products. This category includes continuous furnaces serving forges and presses.

Fig 1 shows the steel production routes from molten metal to semi-finished products, and Fig 2 the range of rolled products obtained from these processes.

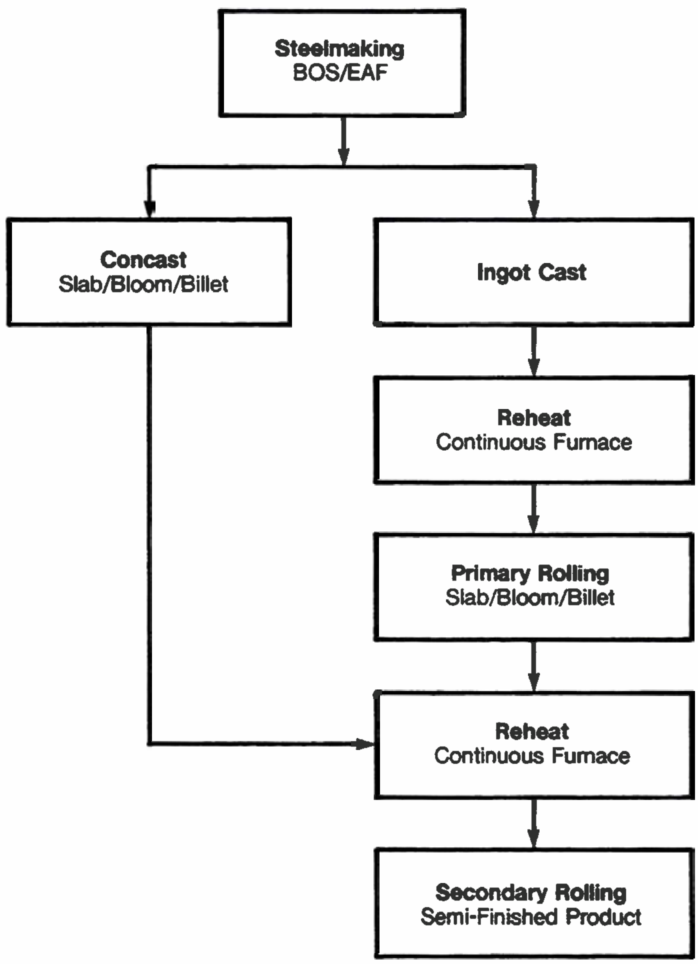

Fig 1 Steel production routes

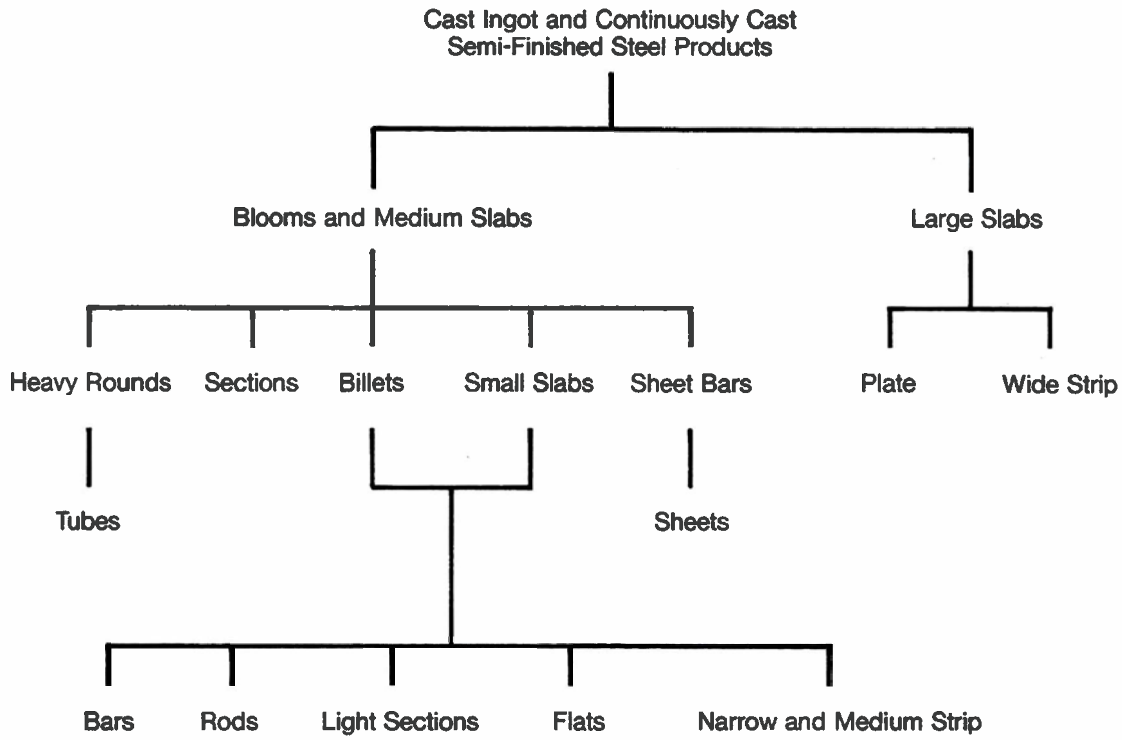

Fig 2 Rolled products

There are currently several hundred continuous reheating furnaces in the UK, of which most have throughput capacities of less than 5 tonnes/hour and are used to reheat components for the engineering industry. However, over 95% of the annual tonnage of reheated steel is processed by less than 70 continuous furnaces with capacities ranging between 40 - 350 tonne/hour.

Specific energy consumption[1] typically ranges between 2.0 GJ/tonne and 3.0 GJ/tonne of steel. However, depending on the actual size, design, operating practice and procedures, the *specific energy consumption* can vary between 0.7 and 6.5 GJ/tonne.

The importance of energy costs on steelmaking, increased competition within the industry both at home and abroad, and an increased environmental awareness has highlighted the importance of energy efficiency. Experience has shown that 'good housekeeping' can achieve fuel savings of around 10%. This suggests that the industry could achieve annual savings of about £8 million through such low cost initiatives. In recent years, savings of up to 50% have been achieved by applying innovative energy saving technologies and advanced control techniques to many furnaces.

Most furnace users could achieve energy savings by:

- improving their knowledge of those aspects of furnace operation and design that contribute to excessive energy usage;
- increasing awareness of their performance and a greater appreciation of that of their competitors;
- increasing commitment to the evaluation of 'proven' energy saving procedures and operating practices;
- having a better understanding of the latest technological developments and the overall cost benefits that these could achieve.

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1 *Words and phases in italics are explained in the Glossary of Terms (Appendix 1)*

More stringent environmental legislation and changes in fuel pricing policies may encourage furnace users to rationalise operations and actively pursue energy efficiency. This Good Practice Guide is intended to heighten awareness of the potential for energy savings and associated cost savings during reheating by considering where and how energy is wasted and describing energy efficiency measures.

Two complimentary Good Practice Guides have been prepared to help users of continuous steel reheating furnaces to save energy. This Guide describes the importance of specification, design and equipment to the energy used in continuous furnaces, and Good Practice Guide 77 describes operational aspects of such furnaces and gives case histories of good furnace operation.

This Guide is in three parts. **Part A** provides the less experienced reader with an introduction to continuous reheating furnaces and explains some of the basic principles of combustion technology and heat transfer.

Part B examines the factors that affect continuous furnaces specifications and describes how these are taken into account in their design and construction. Ways in which design features and equipment can influence energy consumption are highlighted.

Part C presents an action plan which summarises energy-related aspects of furnace design and the measures necessary to reduce energy consumption.

NB: The general heading of continuous reheating furnaces includes those used to reheat steel for forging. Although continuous forge furnaces are not specifically referred to in this Guide, the general principles of design and operation which it describes still apply. Continuous heat treatment furnaces are not considered, because their purpose and often their design are different from those of continuous reheating furnaces used for rolling.

PART A: INTRODUCTION TO CONTINUOUS STEEL REHEATING FURNACES

This section serves as a preface for those readers unfamiliar with continuous reheating furnaces. It provides background information on the function of furnaces and explains some of the principles of combustion and heat transfer.

2. CONTINUOUS STEEL REHEATING FURNACES

2.1 Function

The main function of a reheating furnace is to raise the temperature of a piece of steel, typically to between 900°C and 1300°C, until it is plastic enough to be pressed or rolled to the desired section, size or shape. The furnace must also meet specific requirements and objectives in terms of stock heating rates for metallurgical and productivity reasons. In continuous reheating, the steel stock forms a continuous flow of material and is heated to the desired temperature as it travels through the furnace.

All furnaces possess the features shown in Fig 3:

- a refractory chamber constructed of insulating materials for retaining heat at the high operating temperatures.
- a hearth to support or carry the steel. This can consist of refractory materials or an arrangement of metallic supports that may be water-cooled.
- burners that use liquid or gaseous fuels to raise and maintain the temperature in the chamber. Coal or electricity can be used for reheating, but their use in the UK is limited and is not considered here.
- a method of removing the combustion exhaust gases from the chamber.
- a method of introducing and removing the steel from the chamber. These facilities depend on the size and type of furnace, the shape and size of the steel being processed, and the general layout of the rolling mill. Common systems include roller tables, conveyors, charging machines and furnace pushers.

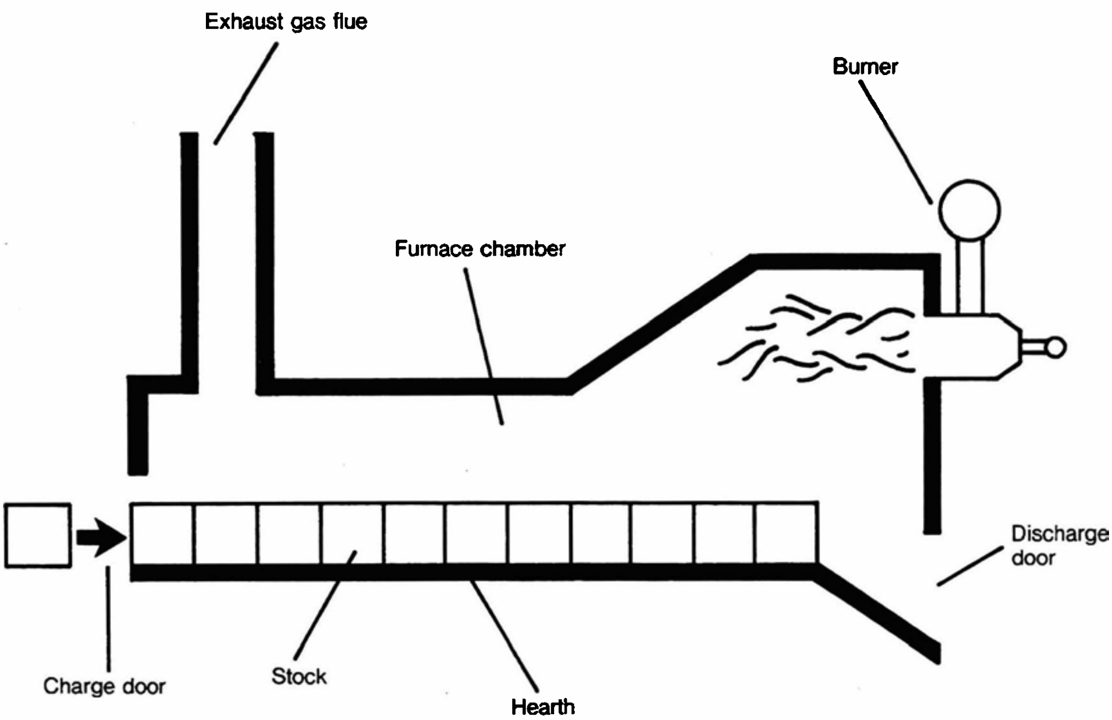


Fig 3 Furnace features

2.2 Historical Development

The development of continuous reheating furnaces is well documented[1-3], with the first pusher type of furnace being built before 1848. These first furnaces and the following generation had sloping hearths to facilitate pushing and were fired at the discharge end. A typical furnace design from the early 1900s is shown in Fig 4(a). This furnace would have used producer gas or coal and had an output of about 25 tonne/hour of 50 mm square-sectioned billets.

In the early 1920s, the two-zone pusher was introduced, Fig 4(b), to satisfy increased customer demand for larger product weights. Furnaces of this type were built with a maximum length of between 30 - 35 metres, which is the limit for avoiding internal pile-ups due to stock buckling.

By the end of the 1930s, the processing of thicker material resulted in the development of the top and bottom fired furnace, Fig 4(c). The stock is heated from above and below while being supported on water-cooled skids. The solid hearth in the soak zone of the furnace allows the steel to reach a uniform temperature, thus minimising the cold spots or skid marks caused by contact with the cooled supports. The three-zone and more recent five-zone furnaces, Fig. 4(d), allowed increased output to be achieved. Present five-zone furnaces are capable of processing 150 mm thick material at 250 tonne/hour.

Designs such as that shown in Fig 4(e) eliminate the effects of water-cooled supports by roof firing along the length of the furnace. There are, however, limitations on the thickness of material that can be heated by roof fired furnaces.

Most multi-zone continuous furnaces are fired from the discharge end so that the flame travels in the opposite direction to the stock movement. A more recent development is the opposed-zone or reverse-fired furnace, Fig 4(f); the first reverse-fired production furnace was built in 1972. The heating zone burners are positioned at the charge end of the furnace, and fire in the same direction as the stock travel, thus increasing heat transfer to the stock. The increased heat transfer allows higher outputs to be achieved compared to a conventional five-zone furnace.

Pusher furnaces have some disadvantages, especially in operational flexibility. In this respect, furnaces with special stock transport mechanisms can be advantageous. The most common of these are the walking beam and walking hearth type.

Walking hearth type furnaces are top-fired only. The stock travels through the furnace supported on eccentrically moving refractory beams which lift the stock above the level of the hearth and deposit it forward of the start position (see Section 5.2.2).

A similar transport mechanism is used in walking beam furnaces (see Section 5.2.4), but these are top and bottom fired and the supporting structure comprises a number of fixed and moving beams which are water cooled in order to maintain their integrity under high furnace operating temperatures. This type of furnace, which was developed in the USA, was first used commercially in the 1960s. It is less common than the pusher type.

There are numerous other furnace types categorised by their method of stock transport. These include continuous recirculation bogie furnaces, barrel type furnaces and rotary hearth furnaces (see Section 5.2.3). These types are less common than pusher and walking beam types because of the limited stock sizes and geometries that can be charged. However, each transport mechanism has its advantages and disadvantages; the final choice is often dictated by the furnace specification and requirements.

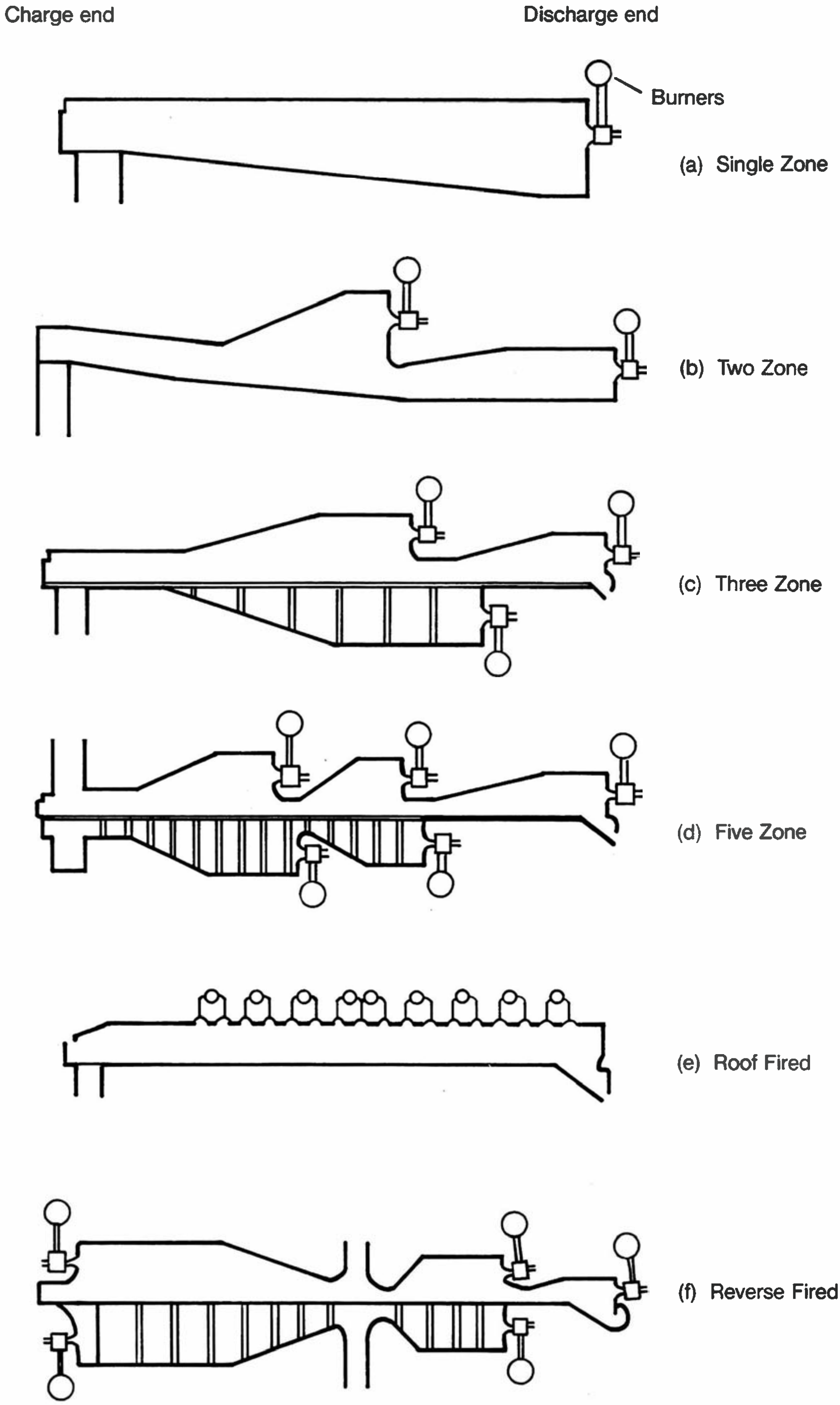


Fig 4 Development of the pusher type furnace

3. FUNDAMENTAL PRINCIPLES OF COMBUSTION AND ENERGY TRANSFER

3.1 Fuels

Fuels are generally classified into three types: solid; liquid; and gaseous. Those fuels found in nature are often referred to as primary fuels and include coal, oil and natural gas. Secondary fuels are those that are manufactured or are by-products of a manufacturing process e.g. coke, gas oil (diesel), blast furnace gas and coke oven gas.

Fuels have complex and numerous constituents, but they all contain one or more of the four basic combustible materials:

1. Solid carbon;
2. Hydrocarbons;
3. Carbon Monoxide;
4. Hydrogen.

Many fuels additionally contain inert materials such as ash, nitrogen, carbon dioxide and water. The composition of some common gaseous and liquid industrial fuels is shown in Tables 1 and 2.

Table 1 Composition of gaseous fuels

Composition %Volume	North Sea (Natural) Gas	Commercial Propane (LPG)	Commercial Butane (LPG)	Blast Furnace Gas	Coke Oven Gas
O_2	–	–	–	–	0.4
N_2	1.5	–	–	56.0	5.6
CO_2	0.2	–	–	17.5	2.0
CO	–	–	–	24.0	7.4
H_2	–	–	–	2.5	54.0
CH_4	94.4	–	0.1	–	28.0
C_2H_6	3.0	1.5	0.5	–	2.6
C_3H_8	0.5	91.0	7.2	–	2.6
C_4H_{10}+	0.4	7.5	91.2	196	2.6
Density, kg/m^3 (stp)	0.763	1.972	2.514	1.340	0.496

Table 2 Composition of liquid fuels

Ultimate Composition % Mass	Gas Oil (Diesel)	Light Fuel Oil	Heavy Fuel Oil
Carbon	86.1	85.6	85.4
Hydrogen	13.2	11.7	11.4
Sulphur	0.7	2.5	2.8
Oxygen, Nitrogen, Ash	–	0.2	0.4
Density, kg/m^3 (15°C)	830	930	960

Natural or North Sea gas is widely used in the UK by both domestic and industrial users. Its main combustible constituent is methane, but it also contains small amounts of ethane, propane, butane and other higher hydrocarbons. The composition of natural gas varies according to its source, but that distributed in the UK is a blend obtained from several North Sea gas wells. This ensures that the marketed fuel is maintained within close compositional limits.

3.2 Combustion

Combustion occurs when oxygen, which is present in air, reacts with the fuel's combustible constituents. The chemical reaction or oxidation results in the development of heat and light. The chemistry of combustion can be described in simple chemical equations such as:

$$C + O_2 = CO_2$$

where carbon combines with oxygen to form carbon dioxide; or

$$2\,H_2 + O_2 = 2\,H_2O$$

where hydrogen combines with oxygen to form water.

In practice, fuel combustion involves unstable intermediates. For methane, the main constituent of natural gas, the combustion process can proceed through 16 possible chemical stages. However, the combustion process can be summarised in a single equation. The combustion reactions for the four main combustible constituents of natural gas can be simply represented as:

Methane: $CH_4 + 2\,O_2 = CO_2 + 2\,H_2O$

Ethane: $2\,C_2H_6 + 7\,O_2 = 4\,CO_2 + 6\,H_2O$

Propane: $C_3H_8 + 5\,O_2 = 3\,CO_2 + 4\,H_2O$

Butane: $2\,C_5H_{10} + 15\,O_2 = 10\,CO_2 + 10\,H_2O$

However, atmospheric air contains oxygen and nitrogen in the ratio 1:3.76 (volume/volume) and in practice, combustion result in the formation of nitrogen oxides (NO_x). The amount of NO_x formed depends principally on the combustion temperature. Liquid fuels also contain small amounts of sulphur (see Table 2) and sulphur oxides (SO_x) are therefore present in their combustion products.

The small amounts of NO_x, SO_x and other compounds present in the combustion gases do not seriously affect furnace performance, but are potentially harmful to the environment. Future and existing environmental legislation relating to furnace emissions may influence furnace design and operation.

Two essential requirements must be met before combustion can occur:

- The composition of the fuel and air (or oxygen) mixture must be within certain limits. Too little or too much fuel in the mixture will prevent ignition (the upper and lower *flammability limits*).
- A minimum temperature must be exceeded before the reaction can occur (*ignition temperature*). In general, all fuel/air mixtures (within their *flammability limits*) will ignite at a minimum temperature of about 650°C.

3.2.1 *Stoichiometric Combustion*

Stoichiometric combustion occurs when the mixture of fuel and air (or oxygen) contains just sufficient oxygen to satisfy the chemical requirements. For example, the complete combustion of one volume of methane requires two volumes of oxygen or 9.52 volumes of dry air for *stoichiometric* combustion. For natural gas the *stoichiometric* air requirement is 9.75 volumes.

In practice, combustion is rarely carried out under *stoichiometric* conditions. The term 'complete combustion' is often used when all the combustion reactions are complete.

This almost always requires more air then the *stoichiometric* requirement. This *excess air* is usually described as the percentage above the *stoichiometric* requirement of the fuel. Thus for one volume of natural gas combusted with 50% excess air there will be:

$$9.75 + (9.75 \times 0.5) = 14.63 \text{ volumes of air}$$

Under *excess air* conditions, the combustion products will contain oxygen. Conventionally the amount of oxygen present is expressed as the percentage by volume of the dry combustion products i.e. excluding any water vapour present.

Figs 5 and 6 show the variation in the products of combustion of natural gas and light and medium fuel oils with the percentage of *stoichiometric* air. The products of combustion are shown on a wet basis (i.e. including the water vapour produced) to give a complete description of the composition of the waste gas.

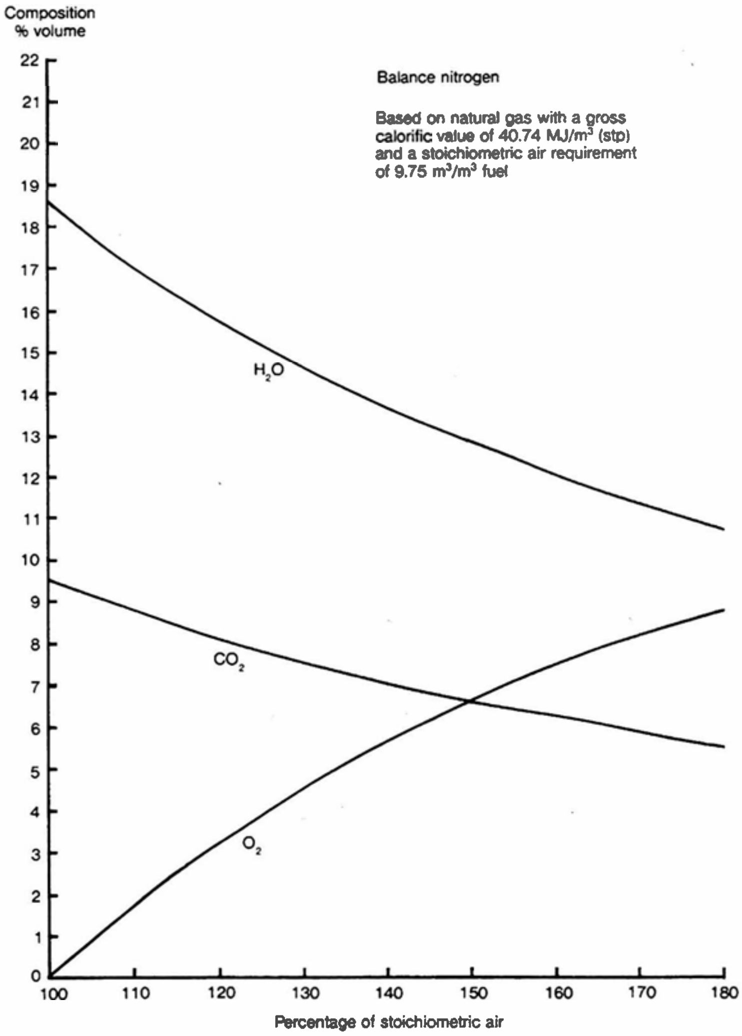


Fig 5 Combustion of natural gas on a wet basis

3.2.2 *Sub-Stoichiometric Combustion*

Combustion may occasionally be described as *sub-stoichiometric* i.e. less air or oxygen is present than required for complete combustion. This may be a deliberate requirement e.g. when a non-oxidising atmosphere is necessary, but is more often due to poor combustion control.

Sub-stoichiometric combustion reactions are complex and depend upon the composition of the fuel, the amount of air and the temperature at which the reactions occur.

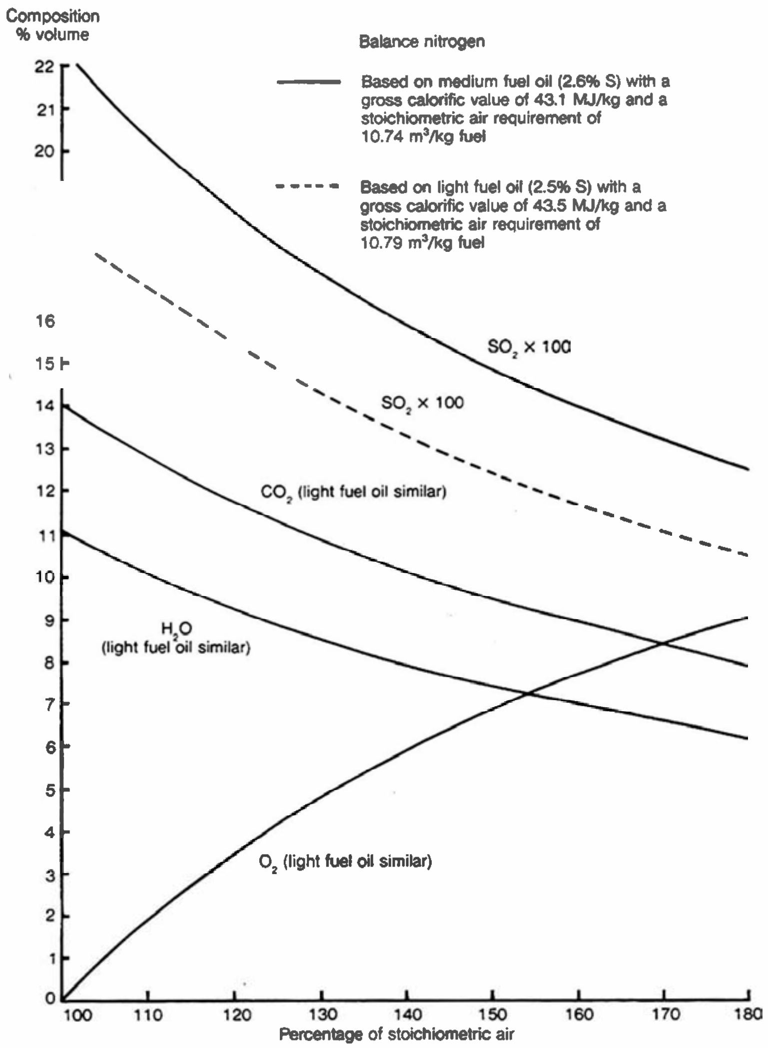


Fig 6 Combustion of light and medium fuel oils on a wet basis

Sub-stoichiometric fuel combustion will generate a waste gas containing mainly carbon dioxide, carbon monoxide, hydrogen, water vapour and nitrogen. Nitrogen oxides (NO_X) will also be present, but only in trace amounts at normal reheating furnace operating temperatures, and SO_X, depending on the fuel used.

The composition of the combustion products when natural gas is burnt under *sub-stoichiometric* conditions is shown in Fig 7. This is presented for information only and has little practical value at the assumed reaction temperature. In reality, it is necessary to calculate the composition under the relevant process conditions.

Burning fuels sub-stoichiometrically is not only unsafe (carbon monoxide is very poisonous), it is also detrimental to the thermal efficiency because the heat content of the combustion products increases when carbon monoxide and hydrogen are present. Fig 8 shows some comparative waste gas heat contents for the combustion of natural gas with *excess air* and a deficiency of air. These illustrate the effect of *sub-stoichiometric* operation. In practice, every effort should be made to ensure that sufficient air is available for complete combustion.

Carbon dioxide will be present in the products of combustion of any carbonaceous fuel, whether it is burned with *excess air* or sub-stoichiometrically. In practice, different conditions can produce the same carbon dioxide level in the combustion products. For example, a carbon dioxide content of 8.2% may indicate an *excess air* level of about 20% or an air deficiency of 30%.

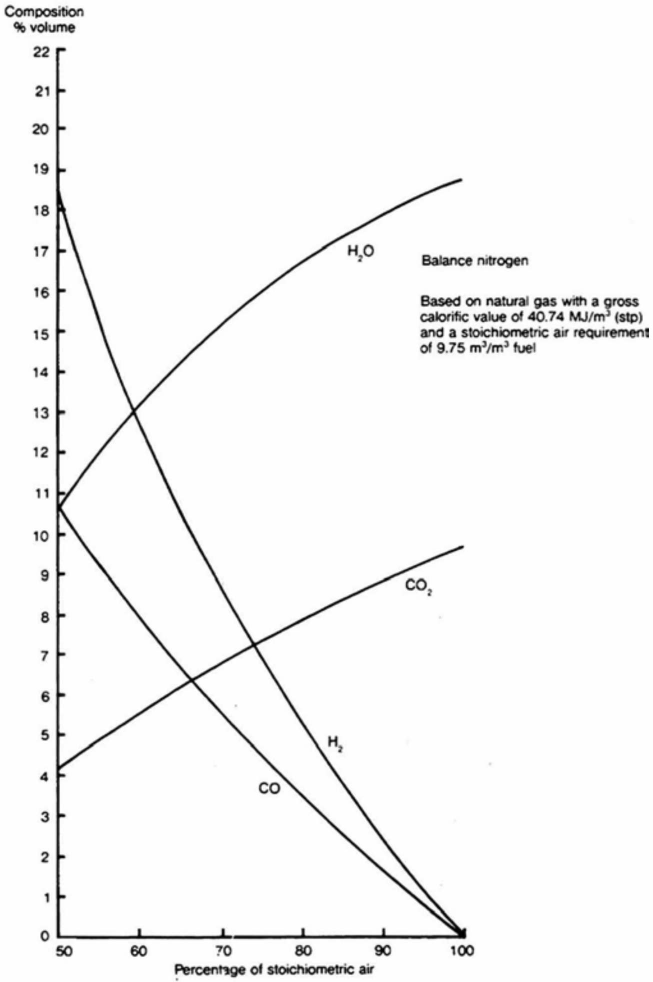


Fig 7 Sub-stoichiometric combustion of natural gas

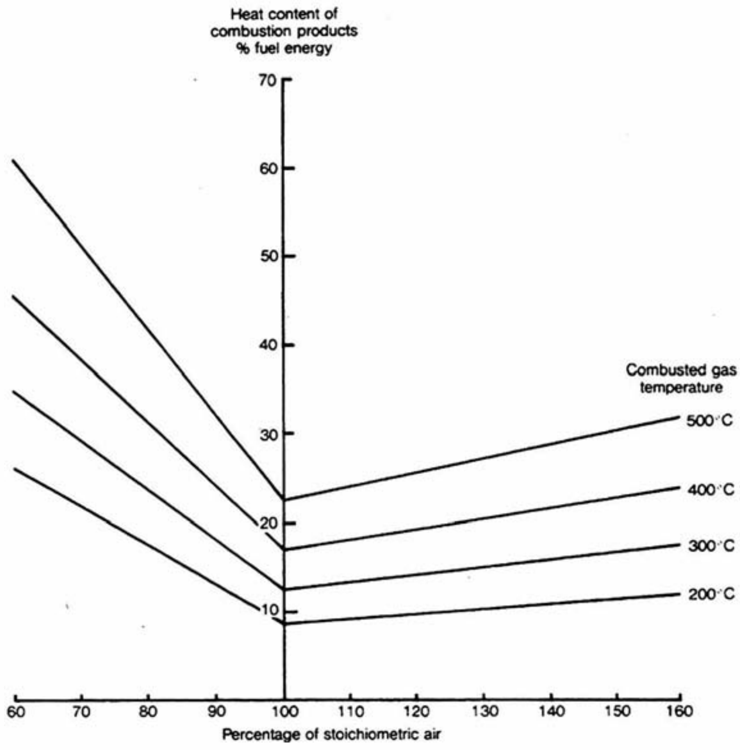


Fig 8 Comparison of heat loss in products of combustion of natural gas burned with a deficiency of air and excess air

Combustion products should be analysed for at least two components to confirm the combustion conditions. The presence of oxygen in the combustion products suggests that complete combustion has occurred and that no carbon monoxide is present. If, however, the distribution and mixing of air and fuel at the burners is poor, complete combustion may not occur even with excess air. Situations can also arise where the flame might impinge on a cool (say water cooled) surface before mixing and combustion are complete. In such cases, the gases may be cooled to below the *ignition temperature*, effectively extinguishing combustion. The partly burned fuel gas will then contain carbon monoxide, carbon dioxide and unreacted oxygen, even though *excess combustion air* may have been provided.

3.2.3 *Combustion with Oxygen Enriched Air*

Combustion is normally carried out using atmospheric air which contains 21% oxygen by volume. The oxygen is utilised in the combustion reactions, but the nitrogen and the small amounts of other gases present are not; these absorb heat which is carried away in the exhaust gases. While the use of pure oxygen rather than air avoids this unnecessary heat loss, it increases the theoretical flame temperature which, in some cases, can exceed metallurgically desirable levels.

One alternative is to use *oxygen enrichment* to reduce exhaust gas heat losses. The enrichment level is typically between 2% and 5%, giving combustion air with an oxygen content of between 23% and 26%. This avoids excessive flame temperatures and reduces the volume of combustion products and the heat losses as shown in Fig 9.

Although combustion with enriched air is not a common practice in reheating furnaces, it can be advantageous in some situations (see Section 4.1.6).

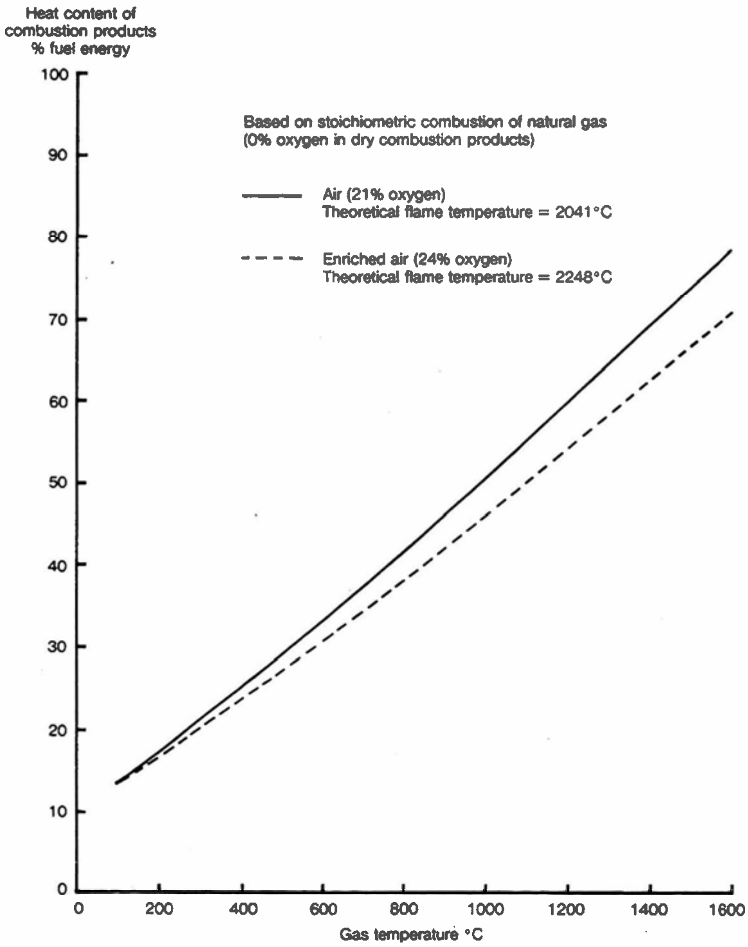


Fig 9 Heat content of combustion products of natural gas

3.3 Calorific Value of Fuels

An understanding of the principles of heat transfer is essential if the fuel is to be used efficiently. It is beyond the scope of this Guide to describe the principles which influence the speed of combustion, *ignition temperature*, flame luminosity, flame development, flame temperature and *flammability limits*. These aspects are well documented[(4-7)]. It is, however, useful to define the heating or *calorific value* of a fuel.

The heat absorbed or given up by a body moving between two temperatures without a change of state is known as *sensible heat*. When a change of state occurs (i.e. from liquid to gas or vice versa) with no change in temperature, the heat absorbed or given up is called the *latent heat*.

The gross *calorific value* of a fuel is the total heat developed by the combustion reactions, at constant pressure, after the products of combustion are cooled to a reference temperature and the water vapour has condensed. It includes both the *sensible heat* and the *latent heat* of the combustion products. If the combustion products are cooled to a reference temperature but the water vapour remains as vapour, then the total heat developed is called the net *calorific value*. Thus the net *calorific value* is merely the *sensible heat* of the combustion products. Table 3 shows the calorific values of the fuels most commonly used in the steel industry.

Table 3 Calorific values of fuels

Fuel		Net Calorific Value	Gross Calorific Value
Coal[1]	MJ/t	29 400	30 450
Coke and Coke Breeze[2]	MJ/t	27 450	27 900
Fuel Oil[3]	MJ/kg	40.5	42.9
Gas Oil	MJ/kg	42.8	45.6
Natural Gas	MJ/m^3	34.82	38.62
LPG[4]	MJ/m^3	86.1	93.1
Coke Oven Gas[5]	MJ/m^3	18.6	20.8
Basic Oxygen Steelmaking Gas[5]	MJ/m^3	8.7	8.9
Blast Furnace Gas[5]	MJ/m^3	3.13	3.18

Notes: *Calorific value* of gaseous fuel based on MJ/m^3 at 15°C and 1 bar pressure

1. Based on medium volatile coking coal (washed smalls)
2. Based on industrial coke
3. Based on heavy fuel oil
4. Based on commercial propane
5. Typical values, subject to compositional variations

The heat content of the combustion products or exhaust gases leaving the furnace depends on its composition and temperature. For a given amount of fuel and combustion air, the lower the temperature of the exhaust gases the lower their heat content. Fig 10 shows the heat content of the combustion products of natural gas expressed as a percentage of the fuel energy input for a range of temperatures and compositions. The heat contained in these gases can be recovered to pre-heat the combustion air and improve efficiency (see Section 7).

All the energy figures given in this guide are based on the gross *calorific value* of the fuels. The oxygen content of the combustion products is based on the dry gas sample.

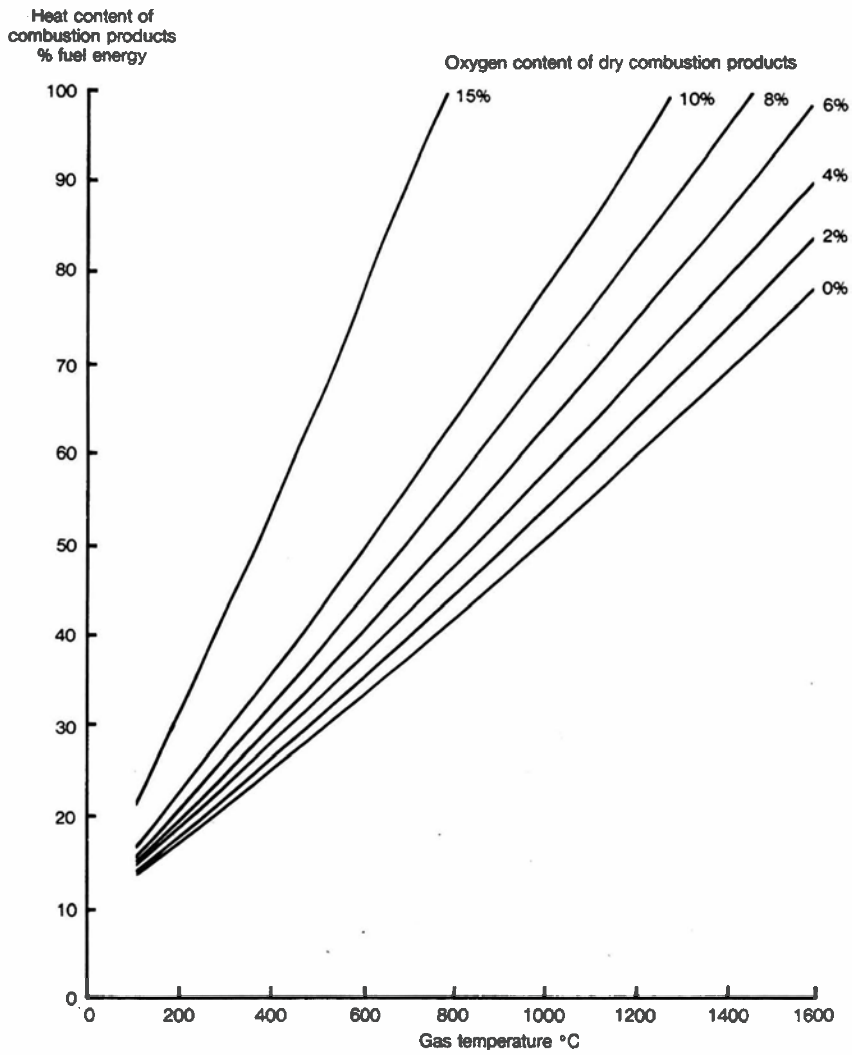


Fig 10 Heat content of combustion products of natural gas with excess air

3.4 Heat Transfer in Furnaces

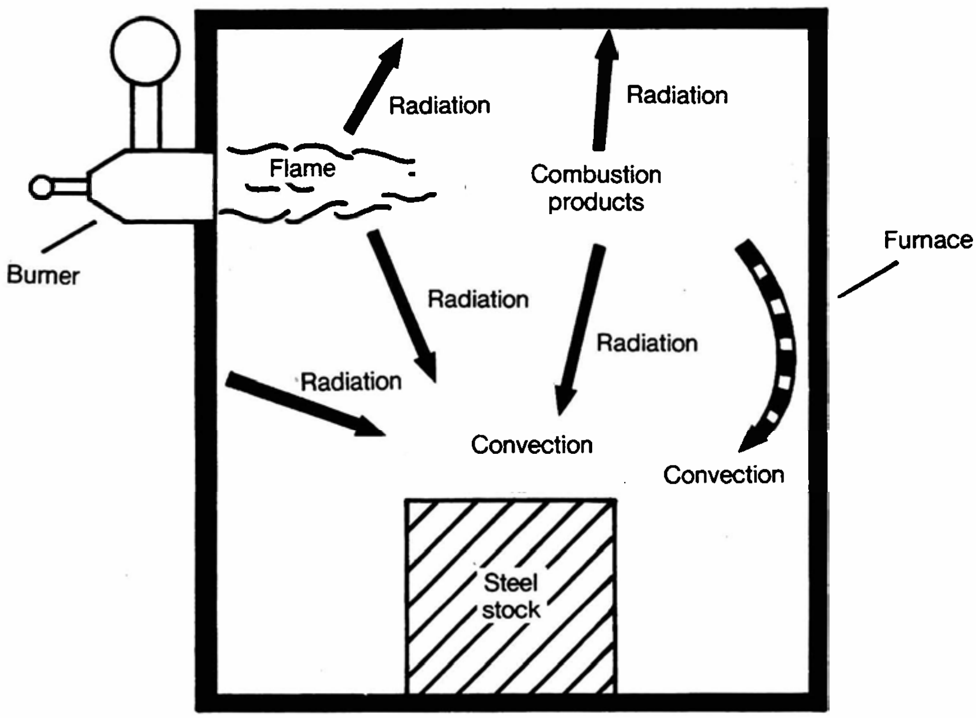
The main ways in which heat is transferred to the steel in a reheating furnace are shown in Fig 11. In simple terms, heat is transferred to the stock by:

- radiation from the flame, hot combustion products and the furnace walls and roof;
- convection due to the movement of hot gases over the stock surface.

At the high temperatures employed in reheating furnaces, the dominant mode of heat transfer is wall radiation (see Fig 12). Heat transfer by gas radiation is dependent on the gas composition (mainly the carbon dioxide and water vapour concentrations), the temperature and the geometry of the furnace.

3.5 Energy Distribution in Furnaces

The performance of a reheating furnace is usually measured in terms of its *specific energy consumption* i.e. energy use/tonnage. This is typically expressed as GJ/tonne or therms/tonne. *Specific energy consumption* is a satisfactory means of comparing furnaces doing exactly the same work and is particularly useful for self-comparison and identifying changes in performance with time. It does not, however, indicate whether the fuel is being used economically or where energy is being wasted.



Heat transfer in furnaces

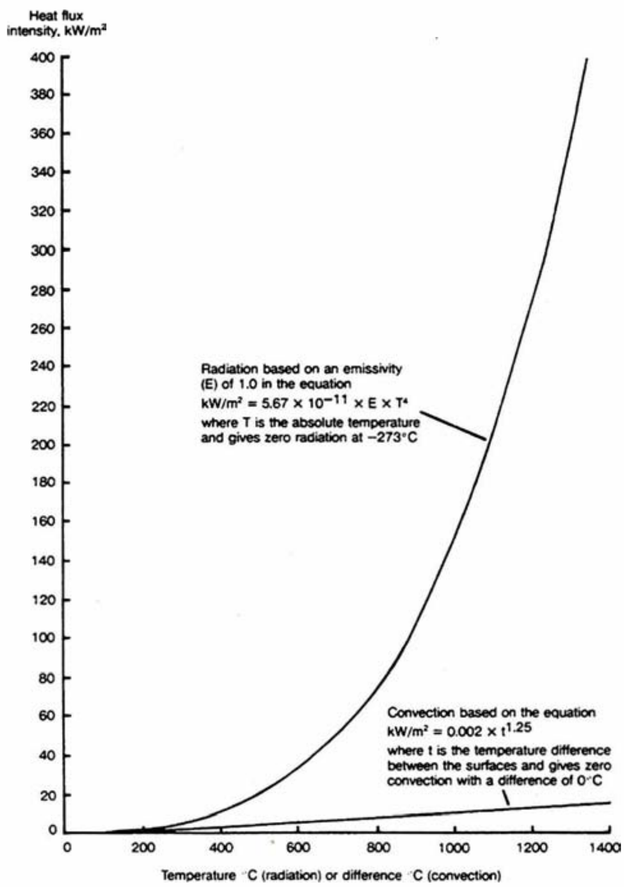


Fig 12 Radiative and convective heat transfer

Calculation of heat or energy balances provides information on the effectiveness of the different parts of the system such as heat uptake by the steel, and heat losses to refractories, water cooled components, etc. A more detailed balance can provide information on the heat losses and heat absorbed in each zone of a multi-zone furnace, but it is not practical to take the numerous measurements required. It is more usual to prepare an overall furnace balance similar to the one shown in Fig 13.

The fuel's energy input is usually calculated by multiplying the amount used by its *calorific value*. If a gaseous fuel is used, the appropriate corrections for temperature and pressure of the metered volume must be made.

Heat uptake by the steel depends on the increase in the temperature of the steel that occurs within the furnace, its specific heat and the total weight processed. The temperature difference within the steel at discharge, any variation in the thermal properties with temperature and the formation of scale must also be taken into account.

Water cooling energy losses can be estimated from the flow rate of the water and its temperature rise for each cooled component.

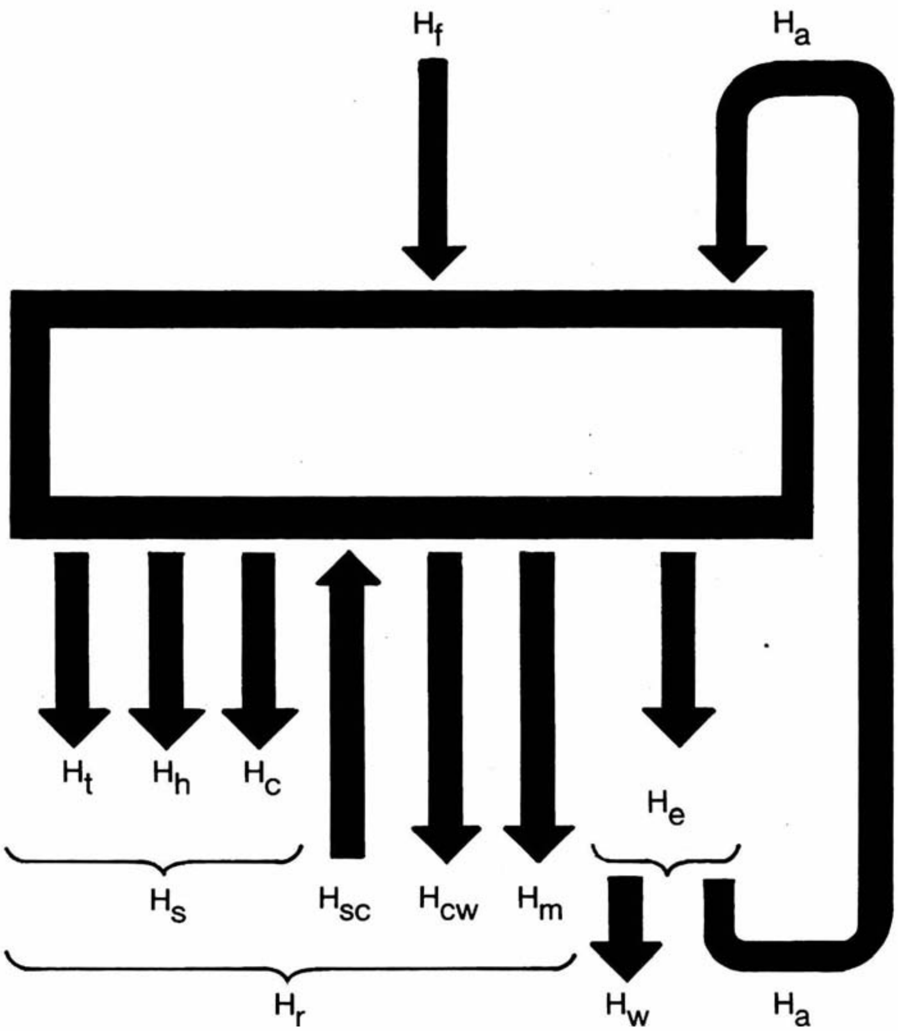
Heat losses to the surroundings by transmission through the refractory structure and by radiation through holes and furnace doors are difficult to quantify accurately because thermal equilibrium or steady state conditions are rarely reached. Heat losses can be estimated using the difference between the known or calculated inputs and outputs, or using measured surface temperatures and areas.

The heat content of the combustion gases leaving the furnace is calculated from the gas composition and temperature.

Depending on the design and operation of the furnace, there may be other elements in the energy balance that need to be taken into account. For example, when steam is used as an atomising medium for a liquid fuel, the heat content of the steam input needs to be estimated.

A complete energy balance can be represented graphically by means of a heat flow diagram or a *Sankey diagram* (see Fig 14). The energy flow is represented by a stream indicating the inputs and outputs; the width of the streams is proportional to the amount of energy.

The term *furnace efficiency* is often used. This is the heat input to the steel expressed as a percentage of the total fuel input. The total *heat released* within the furnace, quoted as a percentage of the total fuel input, is called the *furnace combustion efficiency*.



$$E = 100 \times \left(\frac{H_n}{H_f}\right)\% \text{ or } 100 \times \left(1 + \frac{H_a}{H_f} - \frac{H_e}{H_f}\right)\%$$

$$FE = 100 \times \left(\frac{H_m}{H_f}\right)\%$$

H_f	is heat content of fuel
H_a	is heat content of preheated combustion air
H_r	is total heat release in furnace
H_s	is total heat release to structure
H_t	is heat transmitted through structure
H_h	is heat radiated through holes in structure
H_c	is increase in heat content of structure (storage)
H_{sc}	is heat due to scaling of metal
H_{cw}	is heat absorbed by cooling water
H_m	is heat absorbed by metal
H_e	is heat content of exhaust gases leaving furnace
H_w	is heat content of waste gases
E	is furnace combustion efficiency, %
FE	is furnace efficiency, %

Fig 13 Fundamental energy balance

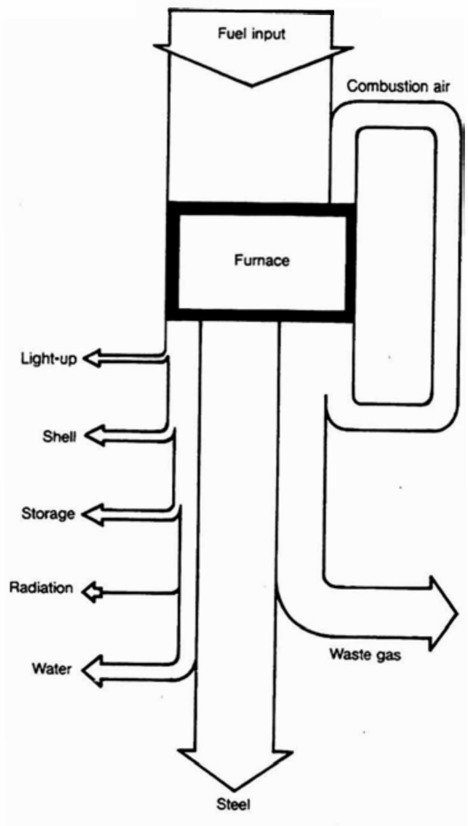


Fig 14 Energy components in reheating furnaces

PART B: FURNACE SPECIFICATION, DESIGN FEATURES AND EQUIPMENT

The furnace specification must be adequately defined if a design is to result in optimum energy use and productivity.

This Guide discusses the specification and design of continuous steel reheating furnaces, but the design principles for batch type furnaces are similar. The cost of a new reheating furnace, which can exceed £1 million, depends on its size and production potential. The importance of the specification and design stage of any proposed installation cannot therefore be understated. Over or under design and the failure to achieve the specified furnace requirements can be costly to correct.

When modifying existing furnaces to improve energy efficiency and/or productivity, the same procedures and considerations should be used as when designing a new installation. The constraints imposed by the existing design will however have to be taken into account, and this may reduce the options available.

Consideration also needs to be given to ancillary equipment. Energy consumption by fans and pumps is often ignored in the evaluation of total energy use; savings can be achieved by the correct selection and design of such equipment (see Good Practice Guide 77, Section 6.6).

4. FURNACE SPECIFICATION

The fundamental purpose of any furnace is to provide the rolling mill with material in a suitable thermal condition for the production of an acceptable and consistent quality product. For this to be achieved at a minimum operating cost, including energy cost, it is essential that flexibility of operation is achievable, together with minimum maintenance requirements and maximum furnace availability.

4.1 Factors Affecting Furnace Specification

The production of an accurate furnace specification requires the following to be clearly defined:

- the shape and size of the stock to be reheated;
- the charge and discharge temperatures of the stock;
- the temperature uniformity of the stock discharged from the furnace;
- throughput rates;
- metallurgical properties.

Furnace features which need to be considered include:

- the option for independent control of stock charging and discharging;
- production scheduling of batch or order sizes, and the continuity of operation;
- capital costs, depreciation, fuel costs, and maintenance costs;
- product yield, including energy losses in scale formation, scale collection and removal;
- the effects of the stock transport mechanism and scale formation on product quality;
- plant constraints e.g. the furnace length available;
- short and long term maintenance requirements, the ease of maintenance, accessibility and the effect on furnace availability.

4.1.1 *Stock*

The range of stock shapes and sizes can impose specific limits on the furnace design. It should be noted that the optimum design is rarely to process the largest piece at the fastest rate.

4.1.2 *Temperature*

The temperature at which the stock leaves the furnace and the temperature difference within the stock dictate the conditions for the next process stage, and have a direct bearing on the yield and quality of the finished product. Stock charge temperatures are important because higher temperatures (hot charging) allows faster heating, a shorter stock residence time in the furnace, and lower energy consumption.

4.1.3 *Throughput Rate*

The tonnage throughput rate must be adequate for other processes to avoid the furnace becoming a 'bottleneck'. In continuous furnaces, it is usual to refer to a maximum steady production rate, even though this may be exceeded for short periods. Designing a furnace to achieve the absolute maximum output rate, and then operating it at a much lower nominal rate can generate excessive energy and other production costs. Under-design can cause the furnace to be a 'rate limiting step' in the overall production process.

4.1.4 *Metallurgical Aspects*

Metallurgical considerations can impose important constraints on the furnace design. They include:

- the maximum tolerable temperature difference in the stock during heating;
- the maximum tolerable rate of stock temperature rise;
- decarburisation;
- scaling.

4.1.5 *Choice of Fuel*

Fuel selection is chiefly related to cost and the reliability of supplies. There is normally a choice of liquid and gaseous fuels, all of which have different and variable costs. The availability and reliability of supplies should be considered, along with historical price trends, and the availability of locally generated fuels such as coke oven gas.

4.1.6 *Oxygen Enrichment*

Oxygen enrichment of the combustion air (see Section 3.2.3) is not a common practice in continuous reheating furnaces. This is because its economic viability is governed by the relative prices of oxygen and the fuel used. The technique does however have several advantages, particularly if increased production is demanded.

Advantages include:

- the ability to use lower *calorific value* fuels in high temperature furnaces;
- better heat transfer owing to the higher flame temperatures;
- waste gases volumes are maintained or reduced at higher productivity levels;
- more flexible control of the furnace atmosphere without prejudicing energy efficiency.

Disadvantages include:

- increased NO_x levels;
- additional maintenance requirements arising from the higher temperatures;
- the inability of furnaces with heat recovery systems to produce the same level of savings as cold combustion air systems.

5. FURNACE DESIGN AND CONSTRUCTION

5.1 Stock Transport Mechanisms

Continuous reheating furnaces are primarily categorised by the method by which stock is transported through the furnace. There are two basic methods:

- Stock is butted together to form a stream or ribbon of material that is pushed through the furnace. Such furnaces are called pusher type furnaces.
- Stock is placed on a moving hearth or supporting structure which transports the steel through the furnace. Such types include walking beam, walking hearth, rotary hearth and continuous recirculating bogie furnaces.

Methods of charging and discharging the stock vary; in certain cases these are simply an extension of the stock transport mechanism. Conveyor systems, charge and discharge machines and gravity discharge are all employed. Charging and discharging techniques generally have no effect on the furnace energy use and the choice of system is usually dictated by stock size and weight, process routes and the location of ancillary equipment. The major consideration with respect to furnace energy use is that the inlet and outlet apertures should be minimal in size and designed to avoid air infiltration. Gravity discharge chutes, which can cause the furnace to act like a chimney drawing cold air in, should be designed with the minimum possible drop.

5.2 Furnace Types

5.2.1 *Pusher Furnaces*

The pusher type furnace is popular in the UK steel industry. It has relatively low installation and maintenance costs compared to moving hearth furnaces. The furnace may have a solid hearth, but it is also possible to push the stock along *skids* with water cooled supports that allow both the top and bottom faces of the stock to be heated. The design of a typical pusher furnace design is shown schematically in Fig 15.

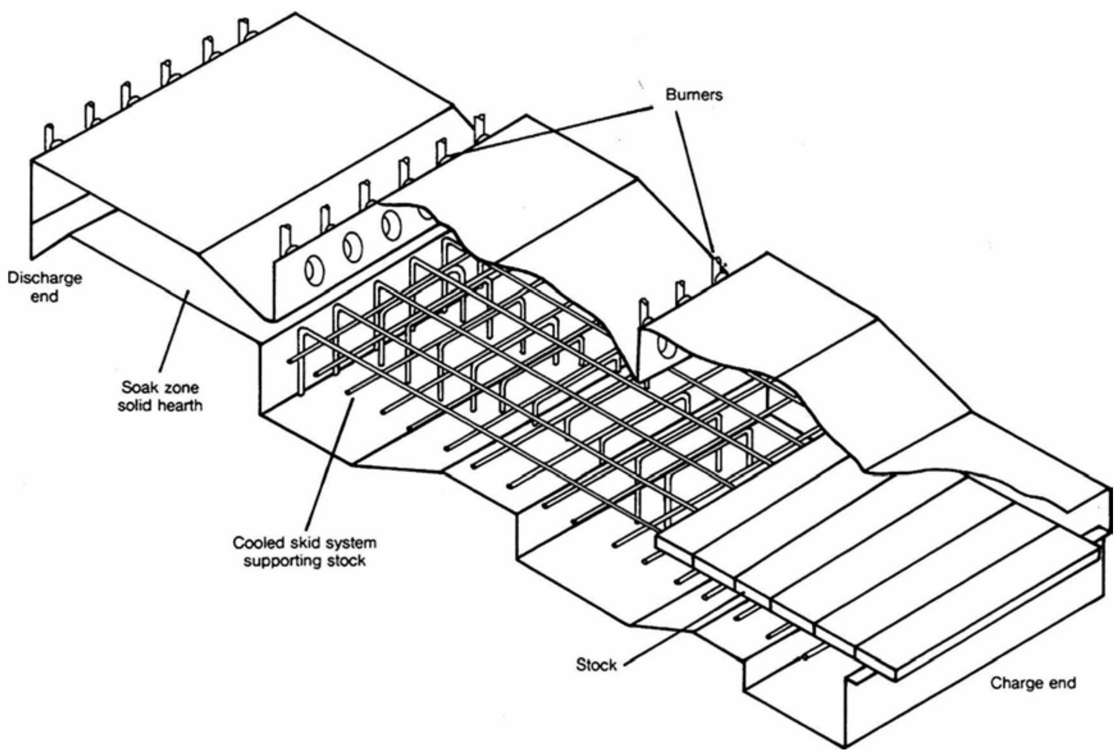


Fig 15 Pusher type furnace

The top and bottom firing achievable in a pusher type furnace has the following advantages:

- faster heating of the stock;
- lower temperature differences within the stock;
- reduced stock residence times;
- shorter furnace lengths compared to solid hearth furnaces.

Pusher type furnaces, however, do have some disadvantages, including:

- water cooling energy losses from the skids and stock supporting structure in top and bottom fired furnaces have a detrimental effect on energy use;
- discharge must be accompanied by charge;
- stock sizes and weights and furnace length are limited by friction and the possibility of stock pile-ups. Top-fired only furnaces often have a sloping hearth to reduce this effect, and lengths are usually less than 35 metres;
- the furnace cannot be completely emptied unless special facilities are provided;
- physical marking of the stock can occur as it is pushed along the hearth or *skids*. 'Skid marks' or temperature differences along the length of the stock in top and bottom fired furnaces can result from contact with or shadowing by the water cooled supports. Both these effects reduce quality levels;
- all round heating of the stock is not possible. This may make it difficult to achieve the desired temperature distribution within the stock at discharge.

5.2.2 *Walking Hearth Furnaces*

The walking hearth furnace (Fig 16) allows the stock to be transported through the furnace in discrete steps.

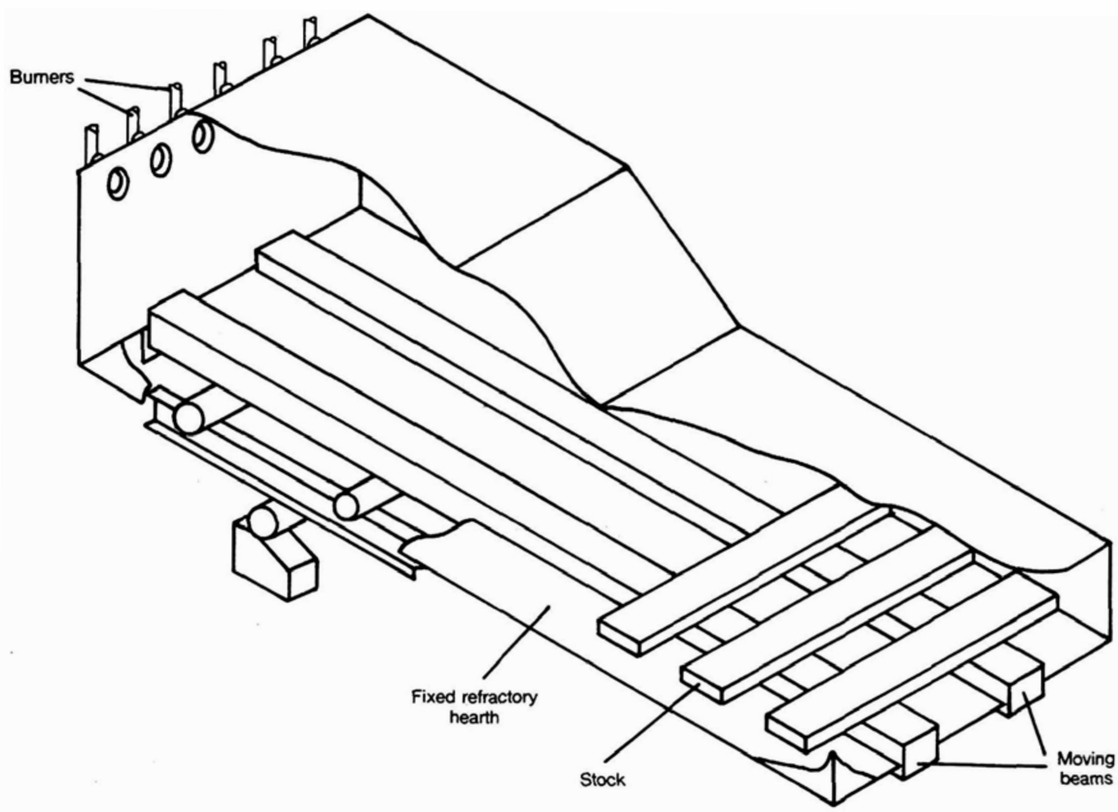


Fig 16 Walking hearth type furnace

Such furnaces have several attractive features, including:

- simplicity of design;
- ease of construction;
- ability to cater for different stock sizes (within limits);
- negligible water cooling energy losses;
- can be emptied;
- minimal physical marking of the stock.

The main disadvantage of walking hearth furnaces is that the bottom face of the stock cannot be heated. This can be alleviated to some extent by maintaining large spaces between pieces of stock, but this means that a longer furnace may be required. Small spaces between the individual stock pieces limits the heating of the side faces and increases the potential for unacceptable temperature differences within the stock at discharge. Consequently, the stock residence time may be long, possibly several hours; this may have an adverse effect on furnace flexibility and the yield may be affected by scaling.

5.2.3 *Continuous Recirculating Bogie and Rotary Hearth Furnaces*

These types of moving hearth type furnaces tend to be used for compact stock of variable size and geometry. In bogie furnaces (Fig 17), the stock is placed on a bogie with a refractory hearth which travels through the furnace with others in the form of a train. The entire furnace length is always occupied by bogies. Bogie furnaces tend to be long and narrow and to suffer from problems arising from inadequate sealing of the gap between the bogies and furnace shell, difficulties in removing scale, and difficulties in firing across a narrow hearth width. The heat loss from the bogies as they recirculate outside the furnace should be considered at the design stage.

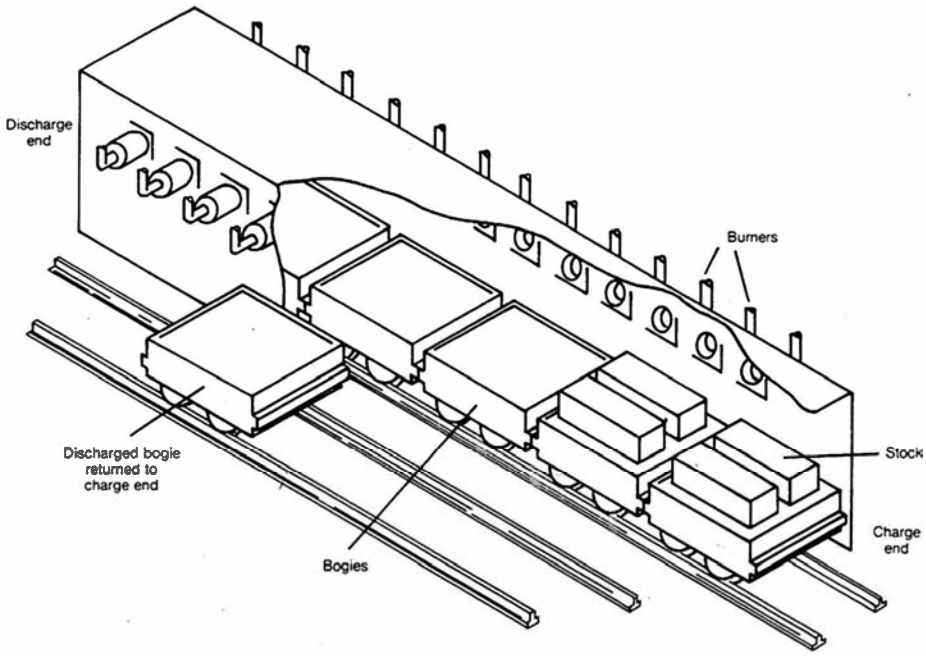


Fig 17 Continuous recirculating bogie type furnace

The rotary hearth furnace (Fig 18), which is a more recent development, has tended to supersede the recirculating bogie type. The heating and cooling effects introduced by the bogies are eliminated, so heat storage losses are less. The rotary hearth has, however, a more complex design with an annular shape and revolving hearth. The special design requirement that the charge and discharge positions are close together can cause logistical problems in the layout of some rolling mills and forges.

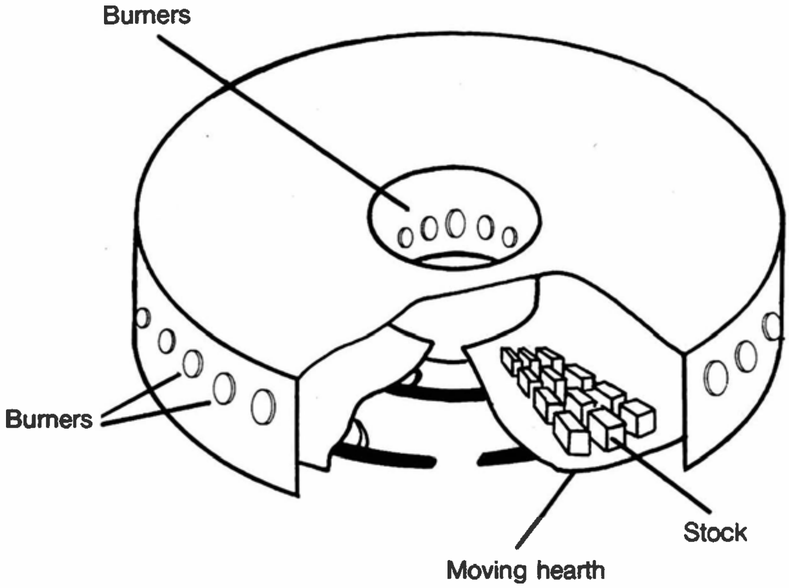


Fig 18 Rotary hearth type furnace

5.2.4 *Walking Beam Furnaces*

The walking beam furnace (Fig 19) overcomes many of the problems of pusher furnaces and permits heating of the bottom face of the stock. This allows shorter stock heating times and furnace lengths, and thus better control of heating rates, uniform stock discharge temperatures and operational flexibility. In common with top and bottom fired pusher furnaces, however, much of the furnace is below the level of the mill; this may be a constraint in some applications. A serious disadvantage of the design is the high water cooling energy losses, which, compared with walking hearth furnaces, can result in a typical increase in *specific energy consumption* of 15%.

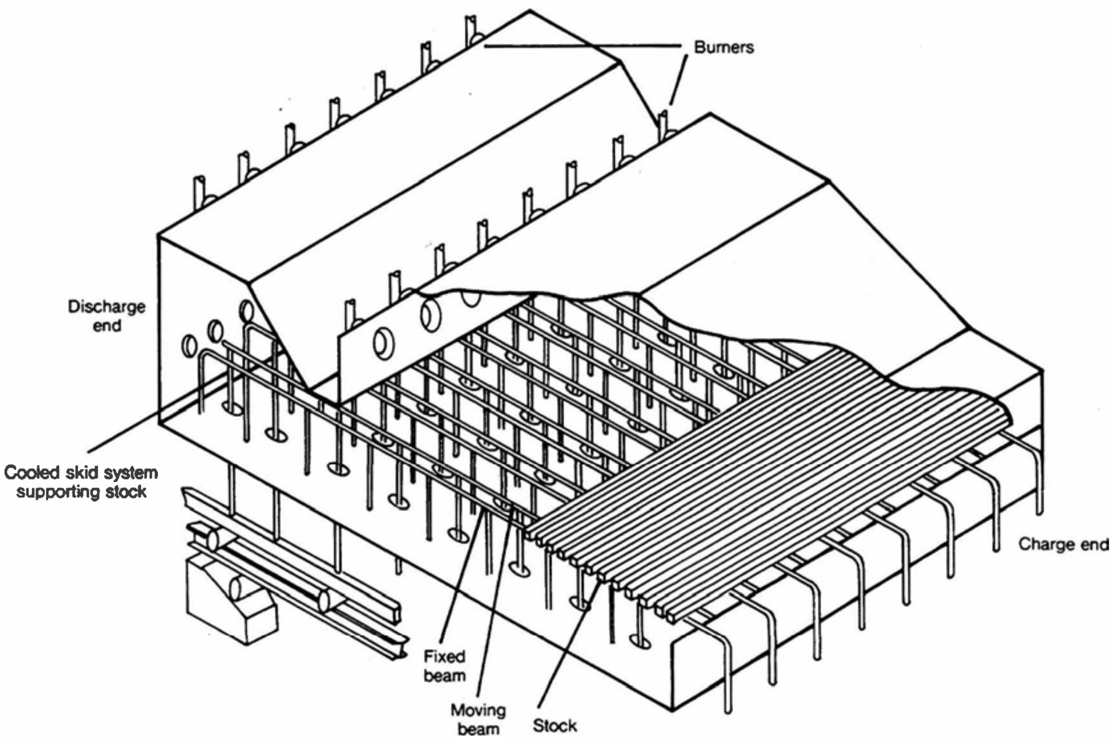


Fig 19 Walking beam type furnace

5.3 Furnace Geometry

The nominal dimensions of a furnace i.e. its width, height and length are primarily dictated by the stock size, heating requirements, method of transport and productivity. Minimising the size of a furnace and hence its surface area so as to reduce heat losses through the refractory shell is not of primary importance in the design stage. The impact of structural energy losses on energy use is generally small compared with heat to steel and cooling water energy losses.

Although the furnace specification imposes limits on its nominal size and shape, it can be refined to include temperature control zones, accommodate burners, optimise gas flow patterns, improve exhaust gas extraction and incorporate a waste heat recovery system.

For example, consider the five-zone pusher furnace design shown in Fig 20. Top and bottom heating has been incorporated to avoid large temperature differences in the stock at discharge, an unacceptably long furnace and a prolonged stock residence time. The limitations of a pusher type furnace can be tolerated in order to simplify the design and operation of the furnace, compared with, for example, a walking beam furnace. The number of temperature controlled zones has been selected to minimise capital expenditure, while satisfying productivity and heating requirements. The width of the furnace is dependent on the stock size, and the *soak zones* are divided accordingly. *Soak zone* width is generally in the range 3 -5 metres. The combustion products are extracted from the furnace at the charge end, which allows heat transfer to the steel by *stock recuperation*.

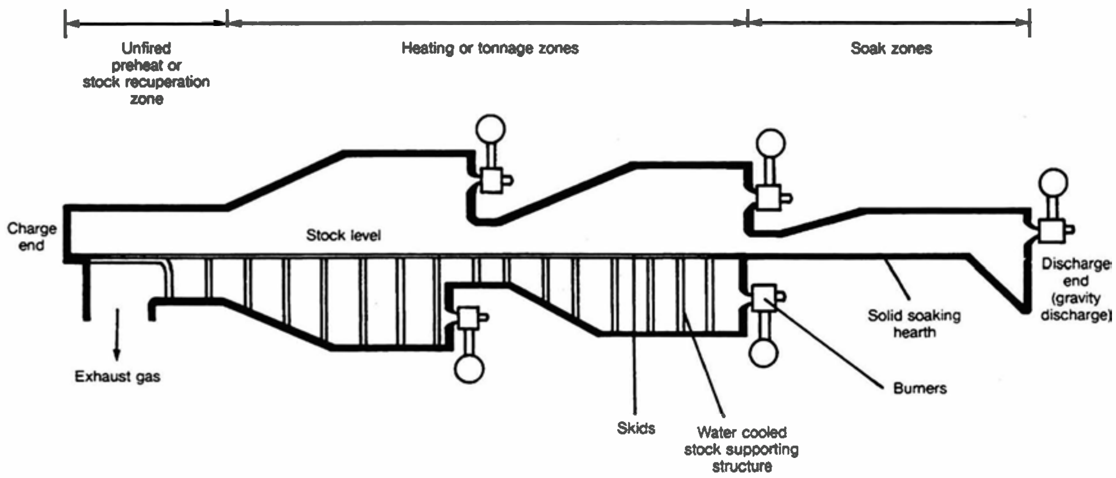


Fig 20 Five-zone pusher furnace

5.4 Firing Technique

After considering the furnace shape and zoning, it is usual to examine burner arrangement and selection. The burner type, size and number depend on the firing technique. This is invariably chosen at the design stage.

Many burner types are available for use with a wide range of gaseous and liquid fuels. Burners often possess the facility to burn at least two types of fuel to allow users to take advantage of different fuel supplies and costs. Burners that are capable of using the hot exhaust gases to pre-heat the combustion air are also available, including regenerative and recuperative types. Such burners offer increased energy efficiency over cold air burners.

The positioning of the burners dictates the gas flow conditions within the furnace, which in turn determine the heat distribution.

5.4.1 *Longitudinal or End Firing*

The pusher type furnace shown in Fig 20 is longitudinally or end fired through purpose-built end walls. The sloping roof and hearth allow the zones to be separated for control purposes and the long pre-heat zone maximises heat transfer within the furnace by both radiation and convection. The firing method allows side-to-side control of the furnace stock temperatures during soaking, but overall furnace control is lengthwise. This is relatively crude and substantial zone interaction is likely.

5.4.2 *Transverse or Side Firing*

An alternative and commonly used technique is transverse or side-firing (Fig 21), which allows control along the furnace length. The burners are staggered (rather opposite each other) to avoid flow instability. There are limitations, however, in using this technique, depending on the type and size of burner and the width of the furnace.

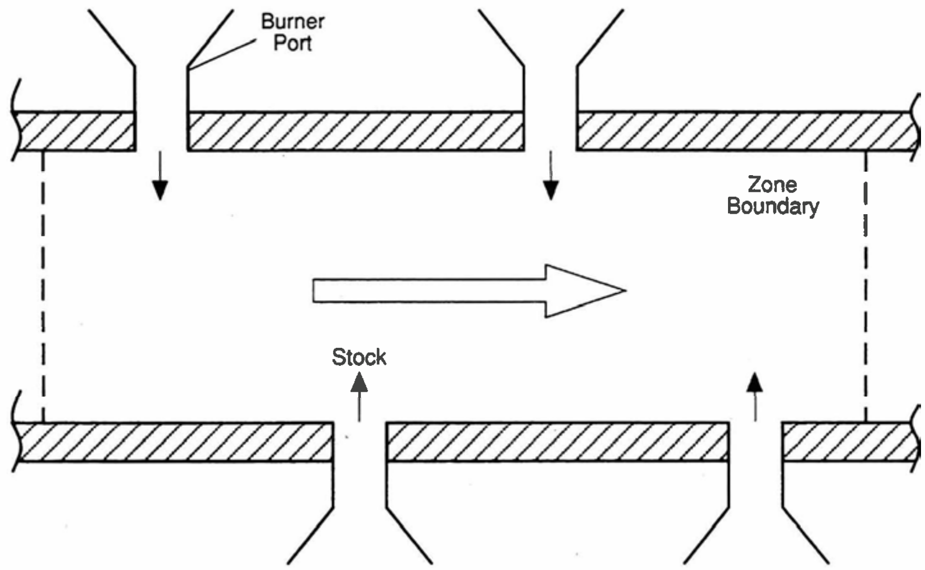


Fig 21 Transverse (side) firing (viewed from the top)

5.4.3 *Roof Firing*

A third method is roof firing (Fig 22) in which specially designed burners are used to produce a short, but wide diameter flame. The flame hugs the roof of the furnace in a circular pattern causing the hot gases to spread out along the adjacent refractory. This flame geometry allows the burner to be positioned close to the stock without the fear of flame impingement, and through radiation, can produce uniform stock heating across the furnace width.

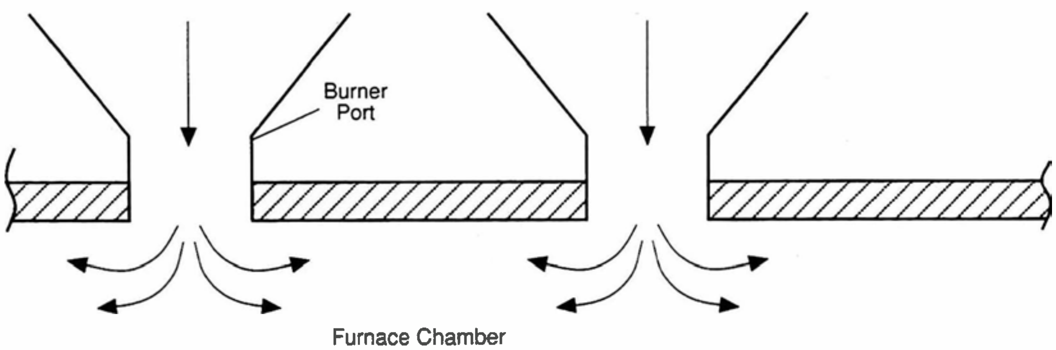


Fig 22 Roof firing (viewed from the side)

This type of burner is generally designed for specific capacities. The flame geometry can be impaired when the burner is turned down, because the flame could develop a forward velocity and increase in length.

Burner arrangements are not necessarily limited to one firing technique; in multi-zone furnaces, both longitudinal and side-firing may be selected.

5.5 Refractories

Insulating refractories which have a high resistance to temperature and wear are used to prevent heat losses through the furnace structure.

Mineral-based refractories are classified according to their chemical composition:

- acid bricks contain at least 92% silicon oxide (SiO_2);
- semi-basic bricks contain at least 65% silicon oxide, but less than 30% alumina (Al_2O_3);
- neutral bricks contain at least 30% alumina;
- basic bricks contain at least 60% magnesium oxide (MgO).
- synthetic refractories e.g. silicon carbide are produced by melting and casting processes.

The structure of the furnace consists mainly of refractory bricks and cement, which must be able to withstand the high furnace temperatures and must be carefully selected and constructed.

The furnace structure may contain *monolithic refractories* which can be shaped *in situ*, e.g. those used for *burner quarls*. There are three basic types of *monolithic refractories*:

- castables;
- mouldables;
- ramming mixtures.

All three types form ceramic bonds as the temperature increases.

Different furnace zones normally operate at different temperatures. The correct selection of refractory materials for the various parts of the furnace and for various components e.g. hearths, walls, etc, is important. This process is governed not only by properties like thermal conductivity, expansion, etc, but also by the experience of the furnace designer or builder.

The hearth is the most important and the most severely treated region of a furnace. It should be able to bear the required load and withstand chemical attack and mechanical wear. The selection of hearth refractories is less critical for top and bottom fired furnaces, than for top fired only pusher types.

For optimum strength and thermal insulation, the walls, roof and hearth of most furnaces are constructed using layers of refractory materials. Thermal insulation is determined by the thermal properties of the refractory, and these properties are important in minimising transmission and storage heat losses. Table 4 compares the thermal properties of typical high density and low density refractory materials.

As discussed in Section 6, structural heat losses can be reduced by using low thermal mass refractory materials in the construction of the furnace. This can be particularly effective if the furnace is subjected to constant temperature variations or frequent stop periods. However, the low strength and operating temperatures of low thermal mass refractories limit their application.

Table 4 Typical refractory properties

Property	High Thermal Mass (High Density Refractories)	Low Thermal Mass (Ceramic Fibre)
Thermal Conductivity, W/m K	1.2	0.3
Specific Heat, J/kg K	1000	1000
Density, kg/m^2	2300	130

6. MINIMISING STRUCTURAL ENERGY LOSSES

The features on the left hand side of the *Sankey diagram* shown in Fig 14 can be classified as structural energy losses. Essentially these comprise:

- heat transmitted through the refractory structure by conduction;
- heat stored in the refractories which is lost when the furnace is cooled;
- energy lost by radiation through openings such as charge and discharge doors;
- energy lost through water cooled components.

These structural energy losses have to be minimised to increase energy efficiency.

6.1 Heat Loss by Conduction

The heat lost by transmission through the refractory structure depends on the types of refractories, their thermal properties, the thickness and the size of the furnace. The walls, roof and hearth of most continuous furnaces are constructed of layers of different refractories for optimum strength and minimum heat loss.

Provided the refractory brickwork is of sound construction and correctly maintained, conduction heat losses should be low. Roofs, in particular, can suffer from escapes of waste gas and hot spots, if gaps are allowed to develop in the brickwork. Monitoring of external furnace shell temperatures using optical pyrometers or thermovision techniques can highlight hot spots and indicate where internal refractories have failed or been damaged. Monitoring should be undertaken regularly.

The total energy lost from a vertical surface by radiation and convection at an ambient temperature of 20°C is shown in Fig 23.

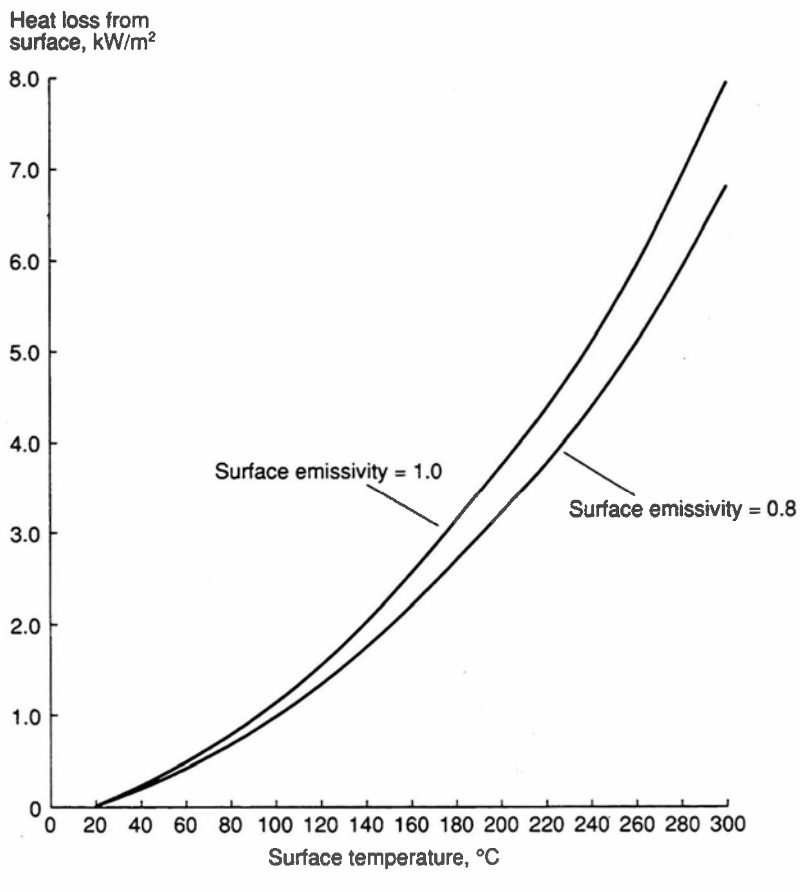


Fig 23 Heat loss from a surface by radiation and convection

This graph demonstrates the importance of minimising surface temperatures, because small increases in wall temperature can result in substantially greater energy losses e.g. an increase in surface temperature from 160°C to 180°C increases the heat loss by 23%. When designing a new furnace, the surface temperature can be included as part of the initial specification; the lowest possible value should be aimed for.

Structural energy losses can be reduced by fitting low thermal mass insulation to the hot or cold faces of the refractory brickwork. However, it is important that this does not result in critical structural components, e.g. roof hangers, overheating.

6.2 Heat Stored in Refractories

Most of the heat stored in the furnace refractories is supplied during the light-up period and the first production shift. Although the refractories may not achieve an equilibrium temperature during a week of continuous operation, the heat input and stored energy is often regarded as negligible following the first production period. However, when down-shift practices are employed, some of the stored energy is lost and has to replaced during the next production period. Other storage losses can occur during steady state production periods e.g. the heat loss from bogies in a continuous bogie furnace.

The amount of stored energy can be reduced by using low thermal mass linings and veneers. Apart from reducing the energy use during production, low thermal mass linings and veneers can also reduce light-up energy and time. The use of such materials should be considered at the design stage. An internal veneer reduces both storage and shell losses, while an external veneer reduces the shell or transmitted loss, but increases storage loss.

The benefits of low thermal mass veneers are illustrated in the following example.

Example

Consider two cases:

Case A. A 300 mm thick high density refractory wall without any additional insulation;
Case B. A 300 mm thick high density refractory wall with a 50 mm thick veneer of ceramic fibre applied to the hot face.

In both Cases the hot face was subjected to radiation from a source (furnace) temperature, as shown in Fig 24.

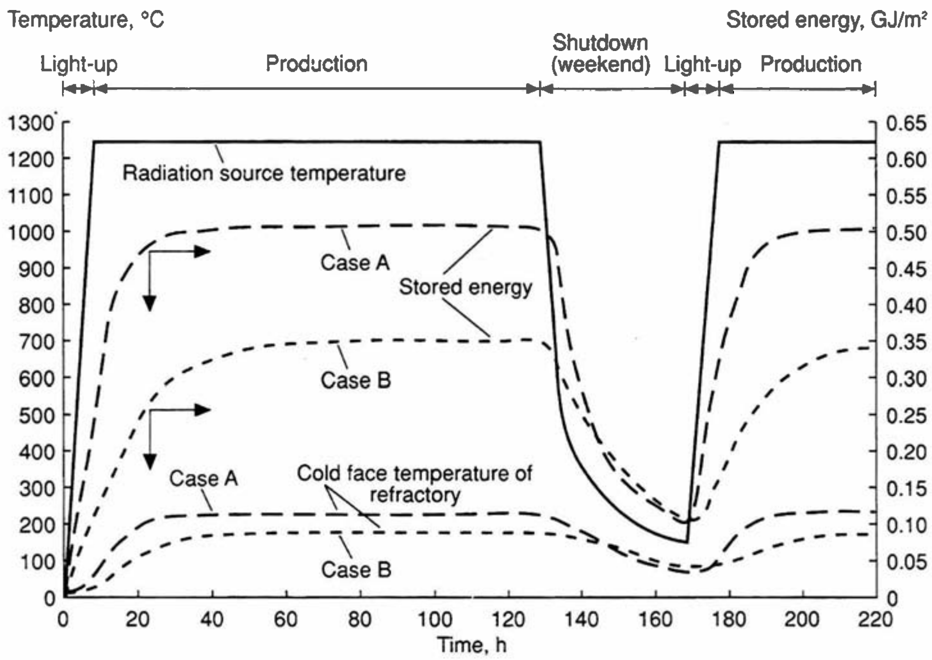


Fig 24 Heat stored in refractories

From a starting 'cold' point of 20°C, the temperature was assumed to increase linearly to 1,250°C over an eight hour (light-up) period.

In Case A, the cold face reached an equilibrium temperature of about 230°C during the productive period. This equates to a heat loss from the surface, by radiation and convection, of 4.0 kW/m^2. The heat stored in the refractories amounts to 0.51 GJ/m^2 (see Table 5).

Table 5 Heat stored and transmitted through vertical refractory walls

Item	Case A	Case B
Dense refractory thickness,mm	300	300
Low thermal mass veneer (hot face) thickness, mm	0	50
Initial wall temperature, °C	20	20
Equilibrium conditions (from cold start)		
Reached after, hours	52	74
Cold face temperature, °C	228	175
Heat loss from cold face, kW/m^2	4.06	2.58
Heat stored, GJ/m^2	0.508	0.348
Minimum cold face temperature at weekend, °C	75	76
Stored energy loss at weekend, GJ/m^2	0.409	0.243

In Case B, the cold face temperature is lower at 180°C and the transmitted energy loss, at equilibrium, decreases to 2.6 kW/m^2; the storage loss being 0.35 GJ/m^2.

During the weekend plant shut-down, most of the heat stored in the refractory for Case A is lost and has to be replaced during light-up for the next production week. For Case B, the stored energy loss is less, implying potential fuel energy savings during light-up and subsequent production shifts.

For Case A, the hot face reaches a temperature of 1,224°C at the end of light-up, and the equilibrium temperature is reached after a total of 22 hours. For Case B, the hot face temperature is 1,242°C at the end of light-up; equilibrium is reached two hours later.

This example demonstrates that the impact of low thermal mass veneers on light-up times and procedures can be significant, with the possibility of reduced light-up times, energy use and overall operating costs.

6.3 Energy Loss by Radiation

Charge and discharge doors are the main sources of energy loss from the furnace by radiation. Although in most continuous furnaces, the radiative heat loss is generally small compared with other losses, it is an area where potential savings are possible. Significant losses can occur even from small apertures because of the high furnace internal temperatures.

Losses can be calculated using the Stefan Boltzman relationship between heat transfer (h) and absolute temperature (T):

$$h = \sigma \varepsilon T^4$$

where ε is the surface emissivity and σ is Stefan's constant (see Fig 12).

At the design stage, it can be beneficial to minimise door areas and/or the charge and discharge door gap. Low thermal mass curtains can be used when doors are necessarily open, provided that excessive mechanical damage caused by contact with the stock can be avoided. During production stoppages, doors should be closed and sealed to prevent unnecessary heat loss. Unless the furnace is to be deliberately cooled for maintenance work to be carried out, doors should also be sealed at weekends to retain heat.

Energy losses by radiation through holes in the refractory structure are almost totally avoidable. Sight holes should be closed, and damaged or missing refractory bricks replaced and repaired. Exhaust gases escaping through openings or air ingress can also affect *furnace efficiency*.

6.4 Water Cooling Energy Losses

Water-cooled components in continuous reheating furnaces represent a significant source of energy loss. There are two types of cooling system. In closed circuit systems, the water is circulated through the cooling elements and to a cooling tower before being recirculated, while in open circuit systems the water is rejected after use. Future environmental legislation could limit the latter, while the former should be carefully designed to avoid both excessive energy use and high recirculation temperatures.

Water cooling is used to protect some components and maintain their physical strength; examples include doors, lintels and the stock transport mechanism or support system. Although doors and lintels generally represent a minor energy loss, the loss through the stock transport system in top and bottom fired furnaces can account for between 6 - 12% of the fuel input under typical operating conditions. As the end of a furnace operating campaign approaches and the insulation of the cooled components begins to degrade, the loss can be as high as 25% of the fuel used. The energy loss as a proportion of the fuel used can also be higher than normal when the furnace is operating at low throughput rates.

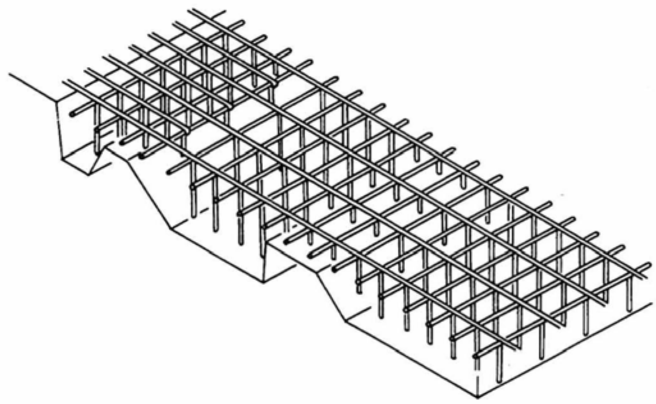
Water-cooled stock transport and support mechanisms, or *skids*, are traditionally insulated with castable refractories, which can also be backed by ceramic fibre to reduce heat loss. Failure of the insulation system exposes the cooled pipes to severe furnace conditions, increasing energy losses and fuel use. The main reasons for insulation failure are:

- *thermal spalling* of the refractories caused by cyclical temperature variations in the furnace;
- thermal stresses caused by high temperature gradients through the refractories, which can be as high as 30°c/mm;
- use of an unsuitable fixing method, e.g. firm attachment of the refractory to the cooled pipes, which can expose it to vibration and bending stresses created by movement of the pipes themselves;
- chemical attack arising from the constituents of the furnace atmosphere (i.e. from the fuel used) or the materials present e.g. scale or slag;
- mechanical damage resulting from movement of the pipe e.g. vibration (particularly in pusher furnaces), expansion at joints and crossovers, abrasion by the stock, etc;
- poor installation.

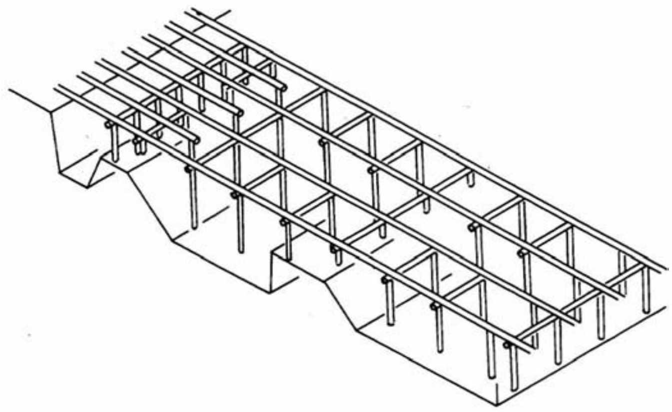
Poor installation has been identified as a major cause of insulation failure. Complex supporting structures are often difficult and time consuming to insulate, and designers should take this into account when drawing up construction and maintenance schedules. If installation, repairs and replacement work are given a low priority and insufficient time, this can lead to premature failure of the insulation or, in extreme cases, of the water-cooled pipe, resulting in lost production and increased maintenance costs.

Water cooling energy losses should be monitored during the operation of the furnace and action taken to correct any deterioration. Refractories should be chosen to suit horizontal and vertical components and to accommodate the various conditions found in different parts of the furnace.

Losses from stock supporting structures can be minimised at the design stage by optimising the number of cooled beams and supports and by using suitable insulation. Fig 25 shows a top and bottom fired pusher type furnace with a rating of 140 tonne/hour. The original water-cooled *skid* system (Fig 25a) was replaced by one with fewer components (Fig 25b). This resulted in a claimed reduction in water cooling energy losses of 26.7 GJ/h (equivalent to a fuel energy saving of 44.5 GJ/h), a 46% reduction in water use, reduced energy use by the pusher mechanism and improved insulation coverage.



(a) Original Skid Layout



(b) New Skid Layout

Fig 25 Pusher type furnace skid arrangement

In some cases, the *skid* cooling energy losses can be used to generate steam (evaporative cooling systems). However, this type of system should only be considered when there is a specific requirement for steam and the efficient operation of the furnace is not affected. When the design assumes that some insulation loss will occur, steam production will alter as the campaign proceeds. This can lead to a shortfall in steam demand or excess steam production depending on the level of insulation coverage.

Minimising cooling water energy losses (or maintaining steam production in evaporative systems) at a specific level requires rigorous maintenance of the insulating system.

7. HEAT RECOVERY FROM EXHAUST GASES

The heat contained in the gases leaving a continuous steel reheating furnace normally constitutes the main energy loss. This should be minimised at the design stage.

There are three basic techniques that should be considered:

- minimising the energy lost in the exhaust gases;
- recycling the exhaust gas energy back to the furnace;
- using the exhaust gas energy for other purposes.

7.1 Minimising Exhaust Gas Energy Loss

The energy lost in the exhaust gases can be minimised by creating a large temperature gradient along the length of the furnace and ensuring that all the exhaust gases are removed at the cold (charge) end. This is usually achieved by incorporating either an unfired *stock recuperation* zone or baffle walls in the design.

7.1.1 *Stock Recuperation*

Stock recuperation involves transferring heat from the hot gases to the furnace and steel stock within the recuperation zone. The longer the *stock recuperation* zone and the lower the roof height above the stock, the lower the temperature of the exhaust gases as they leave the furnace. Under low throughput conditions in multi-zone furnaces, it can be advantageous to turn off zones at the charge end of the furnace in order to increase the length of the *stock recuperation* zone.

7.1.2 *Baffle Walls*

Baffle walls built on the hearth (in top and bottom fired furnaces) or suspended from the roof can, if sized and positioned correctly, can reduce energy use by diverting or channelling the flow of gases within the chamber. Baffle walls increase gas residence times, enlarge the internal areas for heat transfer, avoid direct exhaustion of hot gas streams, and prevent direct radiation heat transfer from the hot to the cold end of the furnace.

Other factors include controlling the combustion air flow (see Section 8.2) and air infiltration into the furnace. Combustion air flow can be controlled using suitable systems and instrumentation. A minimum of 10% *excess air* is advised, in order to comply with the constraints of achieving good combustion of the fuel and satisfying metallurgical requirements. Air infiltration has no merits and should be avoided by appropriate furnace geometry, extraction facilities and pressure control systems.

7.2 Exhaust Gas Energy Recycling

The energy contained in the exhaust gases can be recycled by using it to pre-heat the combustion air. A variety of equipment is available; external recuperators are common, but other techniques are now available such as self-recuperative and regenerative ceramic burners.

For example, with a furnace exhaust gas temperature of 1,000°C, a modern recuperator can pre-heat the combustion air to over 500°C, giving energy savings compared with cold air of up to 30%, as illustrated in Fig 26. Potential savings are even greater with regenerative ceramic burners that can provide pre-heated combustion air at temperatures within 200°C of the exhaust gas temperature, and are also capable of operating with waste gas temp- eratures as high as 1,300°C. It should be noted, however, that the energy savings shown in Fig 26 are theoretical; actual values will be subject to other considerations. The efficiency of regenerative and self-recuperative burners is reduced by inadequate exhaust gas extraction.

Low pre-heat air temperatures then occur. The physical properties of the metals used in recuperators limits inlet gas temperatures to around 1,000°C. At higher temperatures, the need to add cold dilution air reduces the effectiveness of the recuperator.

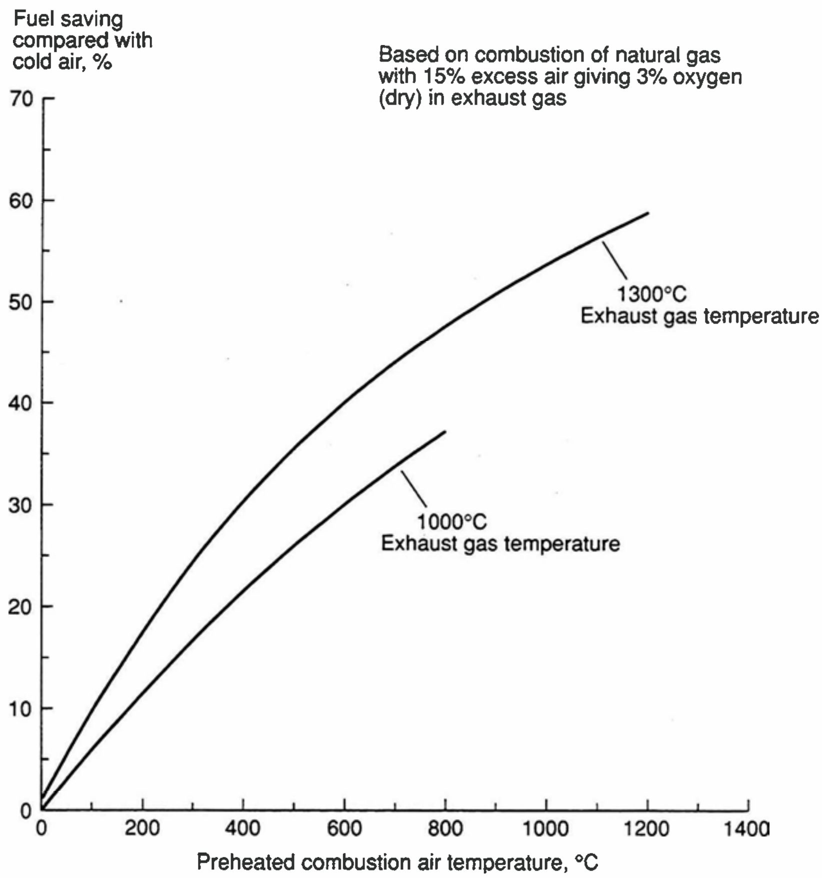


Fig 26 Potential fuel savings with pre-heated combustion air

Heat recovery offers most furnace operators the potential for significant energy savings. The key features of the main forms of heat recovery suitable for continuous reheating furnaces are described below. More details are contained in Good Practice Guide No. 13 - 'Guidance Notes for the Implementation of Heat Recovery from High Temperature Waste Gas Streams'. Gas recuperation (waste heat recovery) is commonly employed in conjunction with *stock recuperation.*

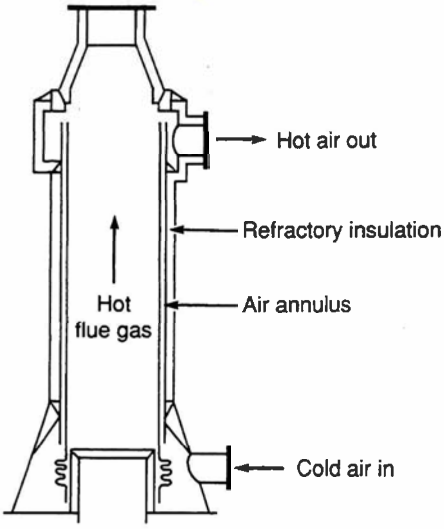
7.2.1 *External Recuperators*

There are two main types of external recuperators:

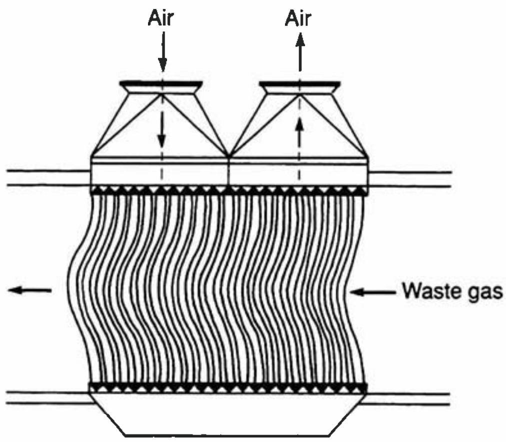
- radiation recuperators;
- convection recuperators.

Radiation recuperators generally take the form of concentric cylinders, in which the combustion air passes through the annulus and the exhaust gases from the furnace pass through the centre, see Fig 27(a). The simple construction means that such recuperators are suitable for use with dirty gases, have a negligible resistance to flow, and can replace the flue or chimney if space is limited. The annulus can be replaced by a ring of vertical tubes, but this design is more difficult to install and maintain. Radiation recuperators rely on radiation from high temperature exhaust gases and should not be employed with exhaust gases at less than about 800°C.

Convection recuperators consist essentially of bundles of drawn or cast tubes, see Fig 27(b). Internal and/or external fins can be added to assist heat transfer. The combustion air normally passes through the tubes and the exhaust gases outside the tubes, but there are some applications where this is reversed. For example, with dirty gases, it is easier to keep the tubes clean if the air flows on the outside. Design variations include 'U' tube and double pass systems. Convection recuperators are more suitable for exhaust gas temperatures of less than about 900°C.



(a) Double Shell Radiation Recuperator



(b) Convection Recuperator

Fig 27 Typical exhaust gas recuperators

The type of recuperator chosen is mainly determined by the exhaust gas temperature under typical operating conditions. Other factors are important, including:

- initial cost;
- operating temperature limits;
- operating pressure and pressure losses;
- reliability and life expectancy;
- ease of maintenance and costs;
- site limitations;
- resistance to wear, chemical attack and corrosion.

When comparing the costs of alternative heat recovery schemes, it is important to consider all essential items and savings. For example, a convection type recuperator is likely to require a chimney, but this may not be so for a radiation recuperator.

Operating temperature limits are usually governed by the materials used to construct the recuperator. The maximum exhaust gas temperature for metal recuperators is about 1,000°C. There are, however, some exceptions e.g. radiation recuperators can accept

temperatures in the region of 1,500°C provided the flow conditions are correct. Most problems arise because of high exhaust gas temperatures and it is often wise to treat manufacturers' specifications with care and to limit exhaust gas temperatures to around 900°C.

Failure to achieve the specified pre-heated combustion air temperature often occurs because operating conditions are not accurately assessed at the design stage. Recuperator performance is influenced by over or under estimated exhaust gas temperatures, non-uniform gas flow (which causes one part of the recuperator to be heated more than another), and heat radiating from the furnace brickwork.

The most common causes of recuperator failure are:

- the use of incorrect design data;
- design errors;
- material and fabrication faults;
- operational faults.

Difficulties often arise because it is necessary to operate at exhaust gas flows that are higher than those specified in the original design. It is usual therefore to design the recuperator to accept about 20% over the anticipated normal capacity. In practice, this margin is often decreased by changes in furnace specification or operating procedures e.g. changing the type of fuel used.

Design errors are typically attributed to the incorrect choice of materials and to inadequate provision for thermal expansion. While faults in the materials used and failures of welds or fabricated components are rare, they have serious consequences in terms of lost production and down-time.

7.2.2 *Self-Recuperative Burners*

Self-recuperative burners (SRBs) are based on traditional heat recovery techniques in that the products of combustion are drawn through a concentric tube recuperator around the burner body and used to pre-heat the combustion air (see Fig 28). A major advantage of this type of system is that it can be retro-fitted to an existing furnace structure to increase production capability without having to alter the existing exhaust gas ducting arrangements.

There is a large variety of commercially-available SRBs, each with performance characteristics suitable for specific applications. There are no known reheating furnace designs using full self-recuperative burner firing, but SRBs have been retro-fitted to some furnaces to pre-heat zones or part of the tonnage zone. SRBs are generally more suited to heat treatment furnaces where exhaust gas temperatures are lower and there are no *stock recuperation* facilities. Fig 29 illustrates the air pre-heat temperatures achievable, and Fig 30 the possible fuel savings compared with cold air, for a range of available SRBs.

7.2.3 *Regenerative Ceramic Burners*

The regenerative ceramic burner (RCB) system consists of two burners, each with a compact regenerator bed containing refractory spheres. While one burner fires, the other acts as the exhaust port; the exhaust gas heats the refractory bed. The system is reversed approximately every 90 seconds so that the combustion air flows through the heated regenerator and is pre-heated, while the combustion products heat the ceramic bed of the other burner (see Fig 31). RCBs can heat the combustion air to within 200°C of the exhaust gas temperature, giving furnace combustion efficiencies of the order of 70%. Waste gas temperatures are normally approximately 150°C. The potential fuel savings obtained by using regenerative burners compared to burners using cold combustion air are shown in Table 6.

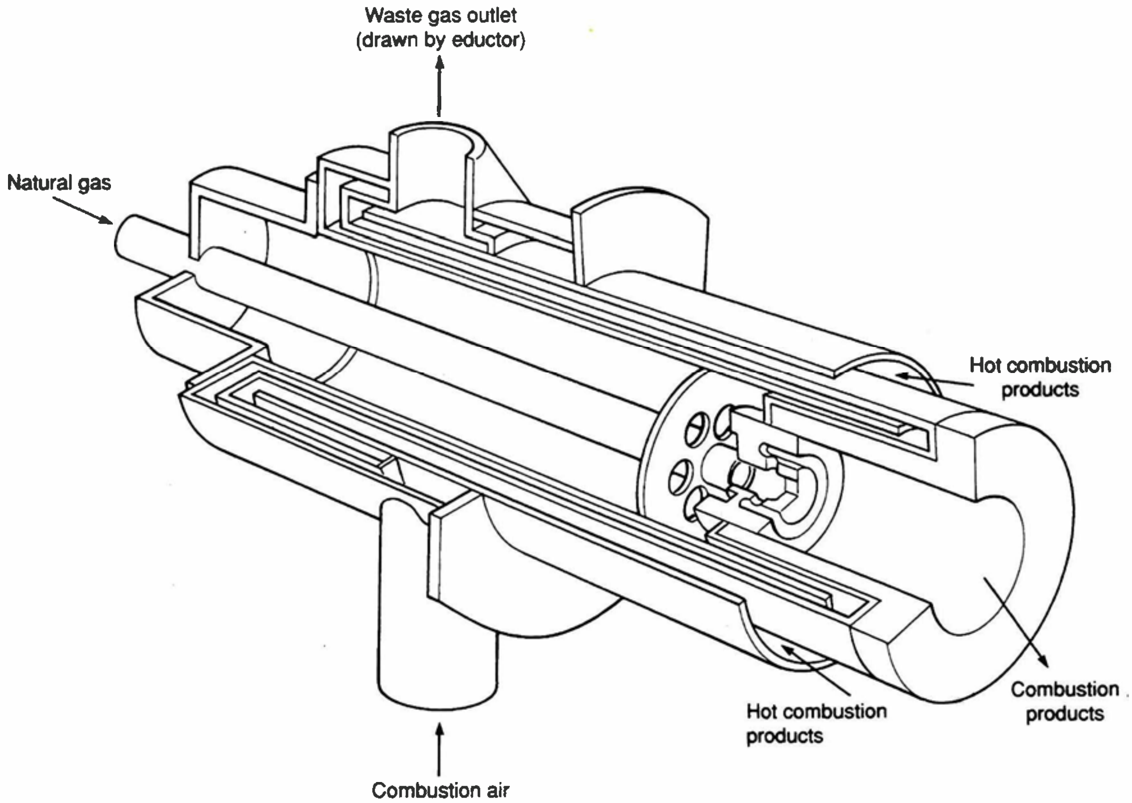


Fig 28 Schematic arrangement of self-recuperative burner

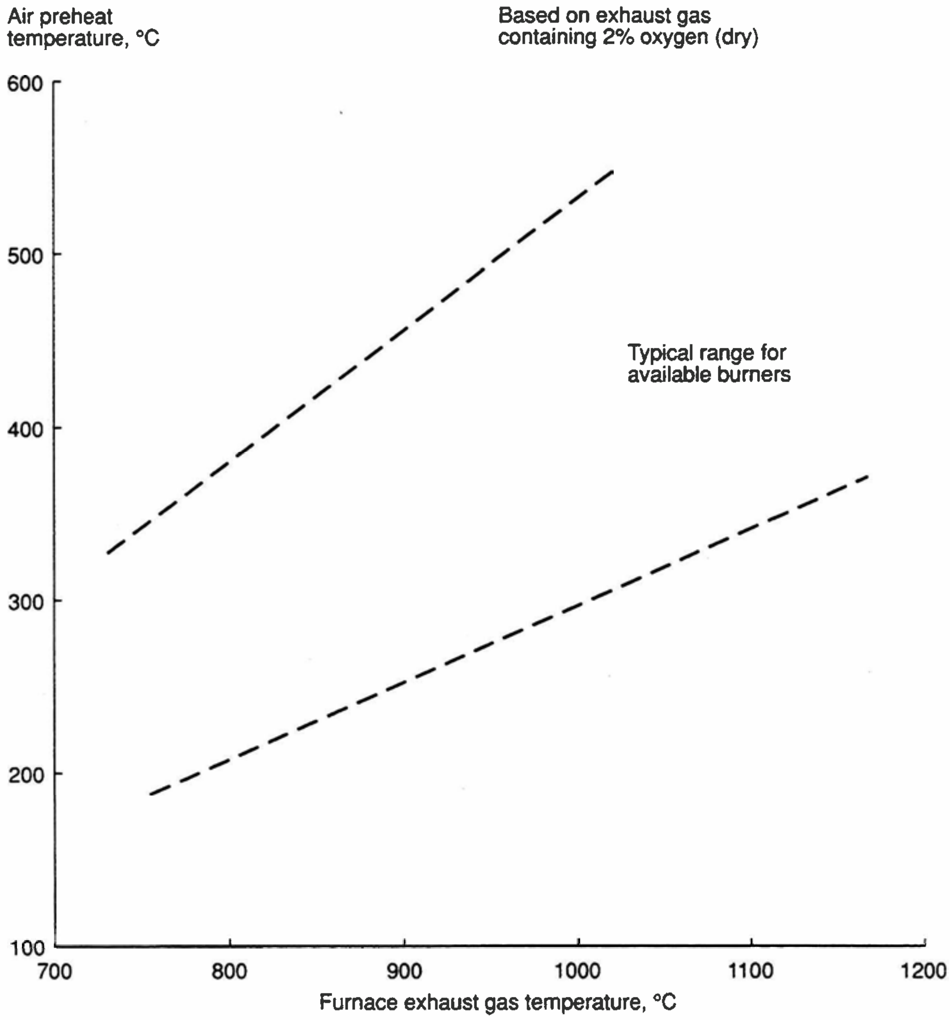


Fig 29 Self-recuperative burner performance

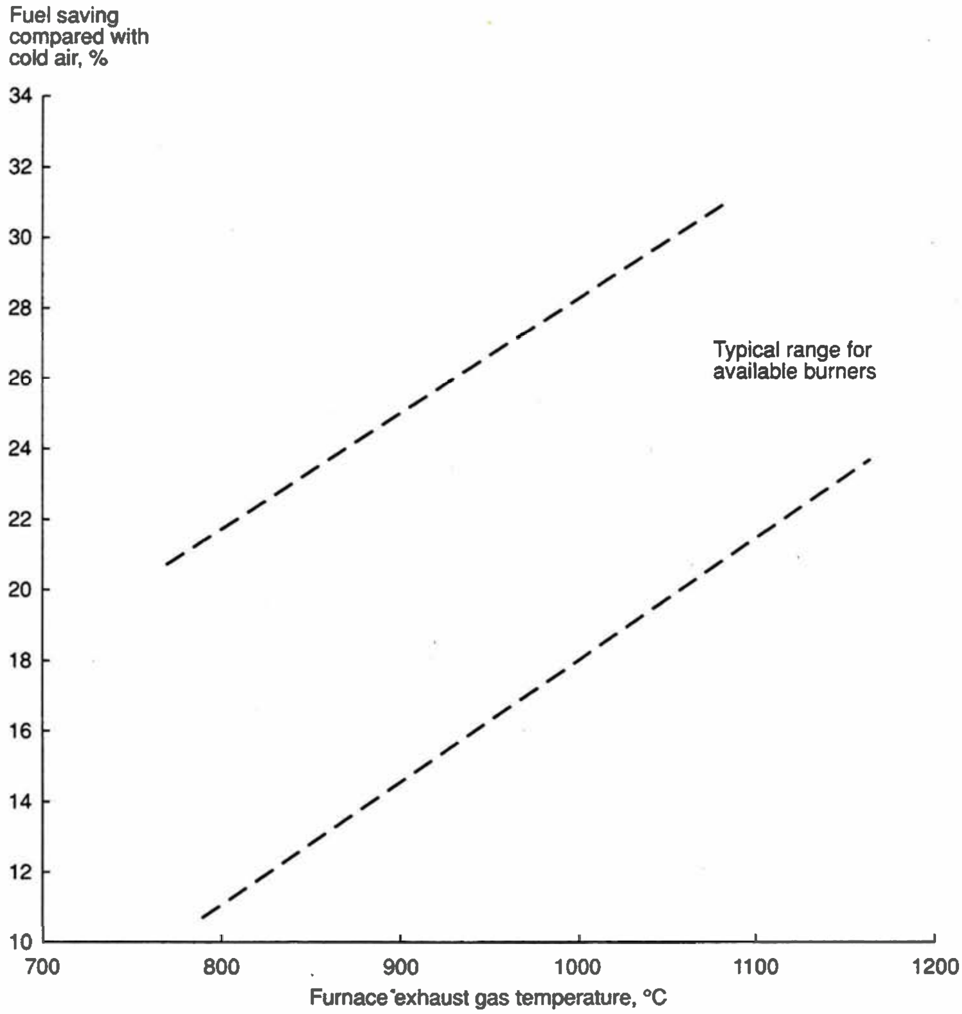


Fig 30 Potential fuel savings compared with cold air with self-recuperative burners

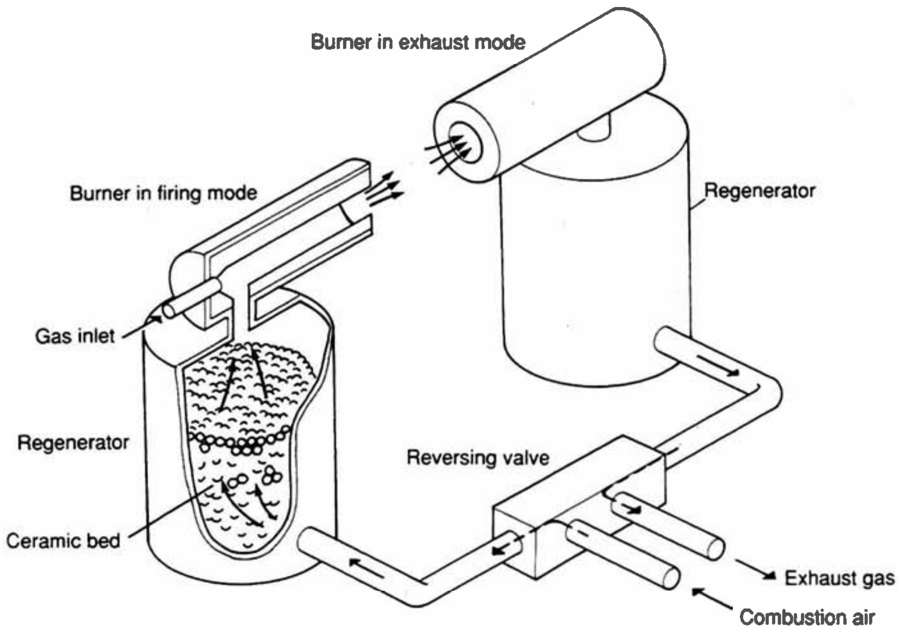


Fig 31 Schematic diagram of regenerative burner firing principle

Table 6 Typical regenerative ceramic burner performance characteristics

Comparison of cold air and regenerative burner systems with natural gas of gross CV 38.1 MJ/m^3, 10% excess air					
Furnace temperature, °C	1000	1100	1200	1300	1400
Average pre-heat temperature, °C	926	990	1082	1171	1298
Average waste gas temperature leaving regenerator, °C	155	160	180	200	220
Regenerative combustion efficiency, %	79.3	78.7	77.3	75.4	74.6
Heat in total waste gas, MJ/h	582.8	626.0	680.0	733.9	798.6
Heat in waste gas to regenerator, MJ/h*	524.5	563.4	611.9	660.5	718.8
Combustion efficiency (cold air), %	46	42	37	32	26
Potential heat in combustion air at furnace temperature, MJ/h	419.1	440.8	483.8	521.1	583.2
Actual heat to air, MJ/h (90% effectiveness)	360.1	396.7	435.4	468.9	524.9
Heat in waste gas leaving regenerator, MJ/h	164.4	166.6	176.5	191.6	193.8
Fuel saved over cold air system (10% excess air), %	42	47	52	58	65

* Approximately 90% of waste gas is drawn through regenerators; the balance is normal leakage through structure. Radiation losses from regenerators, which is minimal, is ignored.

Regenerative ceramic burners have the major advantage of being able to cope with high exhaust gas temperatures (up to 1,350°C) and corrosive exhaust gases. In addition, it is possible to retrofit this system to existing furnaces without adversely affecting energy efficiency. The RCB system has been successfully employed to fire both continuous reheating furnaces and heat treatment furnaces with nominal energy savings of between 30% and 60%.

Using RCBs may require a fundamental change in the approach to using furnace design to satisfy the specification. Exhausting gases through the burners, close to the firing point severely restricts the potential for *stock recuperation*, but this can be offset by the high efficiencies attained. The technique is considered particularly useful for furnaces using warm or hot charged stock.

The high pre-heated combustion air temperatures obtainable with RCBs can lead to increased NO_x emissions. This could limit their use if environmental legislation becomes more stringent. A 'second generation' of burners has been developed which retain the characteristics of RCBs, but with reduced NO_x emissions[8].

7.3 Other Heat Recovery Systems

Another alternative to returning recovered exhaust gas energy to the furnace is to use it for other purposes. There are, however, problems associated with the grade of heat recovered and matching supply with demand. In many cases, external heat recovery by steam generation is no longer considered.

8. FURNACE CONTROL METHODS

Accurate furnace control is essential if energy use is to be minimised and product quality optimised. For new furnaces, it is important that the most suitable control system is specified at an early stage. For existing furnaces, examination of the operating conditions may indicate that improved control methods could be justified economically.

8.1 Furnace Pressure Control

It is important to control the pressure inside a furnace because, if it is below atmospheric pressure, cold air will be drawn into the chamber through doors and openings and conversely, if it is above atmospheric pressure, hot gases will be forced out through the same openings. The escape of hot gases may cause damage to external structural steelwork or penetrate the refractory structure with equally important implications. In the interests of energy efficiency and consistency of operation and product quality, it is, however, desirable to operate the furnace at a slightly positive pressure relative to that of the outside air.

The pressure from the furnace roof to its hearth is not uniform because of the buoyancy effect of the hot gases. Control should therefore be aimed at maintaining the desired pressure at stock level. Pressure is usually sensed by a pressure transmitter; care must be taken to locate the pressure probe within the furnace so that it is free from the direct influence of the burners.

Correct sizing of the exhaust gas flue area and height is essential if proper pressure control is to be achieved. Converting a furnace from one fuel to another can cause problems in this respect, because different fuels produce different volumes of combustion products. Incorrect chimney or flue stack heights can reduce or increase suction, thus causing difficulties in control.

8.2 Air/Fuel Ratio Control

The air/fuel ratio control system regulates the quality of combustion. The burners and control system should be chosen in accordance with the tolerable limits of combustion quality acceptable for particular processes. Under most circumstances, a moderate degree of control is required to ensure flame stability and complete combustion of the fuel, while close control is necessary to optimise fuel efficiency by operating as close as possible to *stoichiometric* conditions so as to minimise exhaust gas energy losses. In practice, metallurgical properties may dictate the minimum acceptable air/fuel ratio needed to achieve the furnace atmospheric composition necessary to provide the degree of scaling and decarburisation required.

The significance of satisfactory air/fuel ratio control in achieving optimum fuel efficiency is demonstrated in Fig 32. An air/fuel ratio for natural gas of 15:1 is equivalent to an *excess combustion air* level of 54% and an oxygen concentration in the waste gases of about 8.0%. Assuming cold combustion air is used, a furnace operating with burners under these conditions and an exhaust gas temperature of 900°C would have a *combustion efficiency* of about 37% i.e. 63% of the fuel energy input is contained in the exhaust gases. With no heat recovery this energy is wasted. If the air/fuel ratio is adjusted to give 2% oxygen in the waste gases, the exhaust gases at the same temperature would contain 49% of the fuel's energy. This represents a fuel saving of 37% for the same heat release within the furnace. With pre-heated combustion air, the benefits obtained by optimising air/fuel ratios decrease with increasing pre-heat temperature.

The techniques used to control air/fuel ratios depend on the type of burner, the range of firing rates, pre-heated air conditions and the mode of process control (on/off, high/low, modulating, etc). The arrangement of individual control components, valves and governors, which form the valve train is important and there are specific requirements to ensure safe operation[9-16].

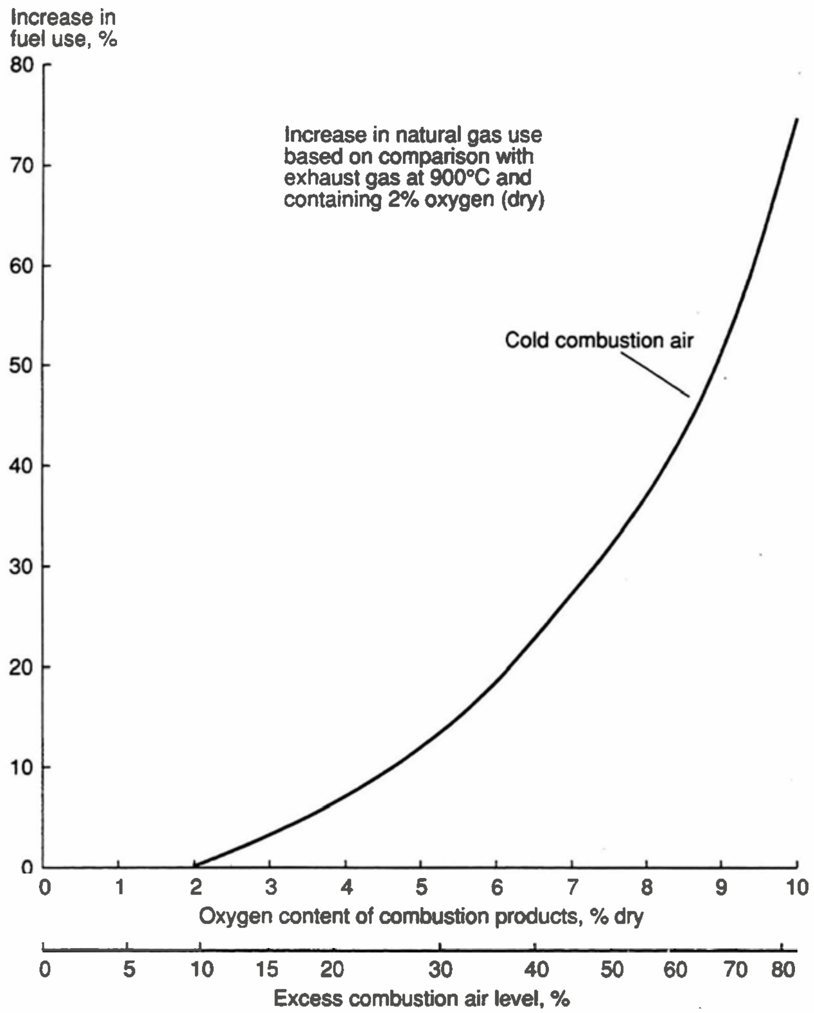


Fig 32 Effect on fuel use of increasing excess combustion air levels

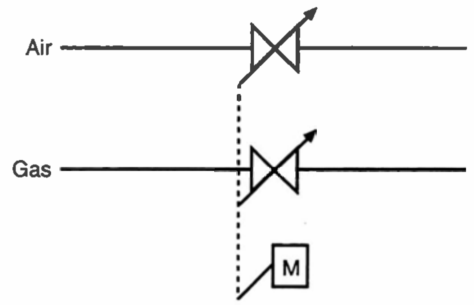
The air/fuel ratio control systems described briefly here are applicable to *nozzle mix burner* systems (rather than *premix burners*) and are suitable for use with gaseous fuels. The techniques used for ratio control using oil are similar, but it must be remembered that oil or dual fuel (gas or oil) burners require more complex control systems because of the need for pumping as well as accurate control of oil temperature and pressure.

8.2.1 *Ganged Valve Assembly*

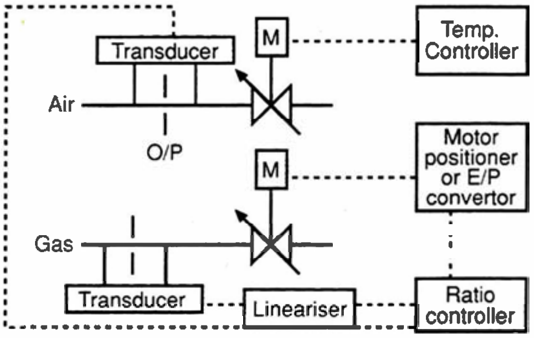
The simplest method of air/gas ratio control is to use mechanically linked valves in each of the gas and air supply lines as shown in Fig 33(a). Butterfly valves provide an inexpensive method of control, suitable for high/low process control modes. Alternatively port valves can be used which, if correctly designed and installed, will proportion the flows of air and gas (or oil) throughout the burner firing range.

8.2.2 *Cascade Control*

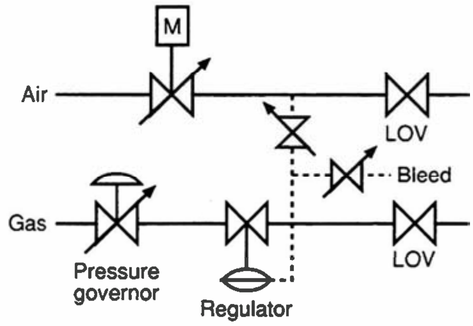
Some industrial flow ratio controllers are based on measurement of the differential pressures across orifice plates or venturi flow meters fitted in the air and fuel supply lines. The differential pressures are sensed by a ratio controller and action is taken to correct any change by adjusting a valve in either the air or fuel line. If the flow control valve is in the air line, the system is generally referred to as an air lead, and in the fuel line as a fuel lead. Controlling the ratio based on the measurement of flow will result in errors as the flow reduces (with a loss of ratio), because of the relative characteristics of the flow metering devices. The control signals will additionally need compensation when metering pre-heated combustion air. An example of the cascade control system is shown in Fig 33(b).



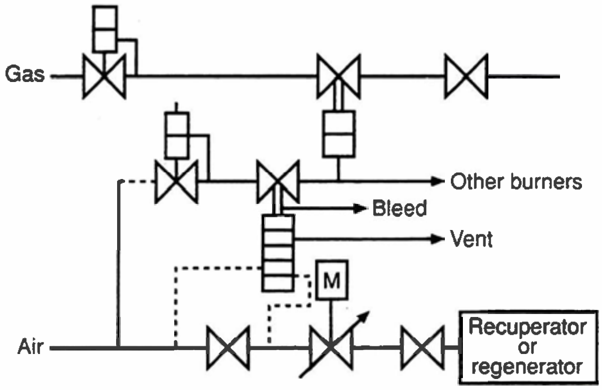
(a) Simple Ganged Valve Assembly



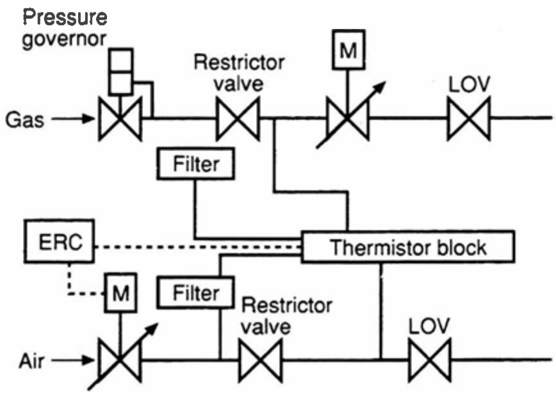
(b) Cascade Control (Air Lead)



(c) Pressure Divider Technique (Simple Impulse Regulator System)



(d) Multiplying Regulator System



(e) Electronic Ratio Control

Fig 33 Air/fuel ratio control systems

8.2.3 *Pressure Divider Technique*

In the system shown in Fig 33(c), an impulse pressure from the air line is fed to the zero governor in the gas line. This controls the gas flow by maintaining a gas pressure equal to that of the impulsed air pressure in order to balance the system. The air and gas pressures then modulate at equal values and ratio throughout the range. The system requires regular maintenance of the bleed valves and is not suitable for pre-heated air systems.

8.2.4 *Multiplying Regulators*

When the combustion air is pre-heated, for example with self-recuperative and regenerative burners, a multiplying regulator must be used. A measurement of the cold air flow (differential pressure across an orifice plate or restrictor) is used to impulse a regulator that controls the gas flow, see Fig 33(d).

8.2.5 *Electronic Ratio Control*

When electronic ratio control is employed, the differential pressure across restrictors in the air and gas (or oil) lines induces flows through a thermal resistor or thermistor block, as shown in Fig 33(e). This block contains two matched thermistors which exhibit large variations of electrical resistance with temperature. The thermistors are arranged in the form of a bridge circuit, and the output is processed by an electronic module. If the gas flow increases, the pressure drop across the restrictor increases and induces a large flow across the thermistor in the gas line which cools the thermistor and increases its electrical resistance. The control module increases the air flow to produce an equivalent electrical resistance in the other thermistor, thus maintaining the air/fuel ratio. The technique has a rapid response and allows high turn-down ratios, of up to 10:1, to be achieved.

8.2.6 *Oxygen Trim Control*

Measurements of the oxygen concentration of the combustion products in the furnace can be used to provide a signal to trim air/fuel ratio control systems. A system using zirconia-based oxygen measuring cells has been successfully used in oil and gas fired furnaces. Careful siting of the measuring probes is necessary to avoid flame paths (see Good Practice Guide 77, Section 6.3.)

8.3 Temperature Control

Most continuous reheating furnaces employ some form of independent zone temperature control. In the absence of temperature control, product quality is not controlled, refractory damage can occur, exhaust gas temperatures will be high and fuel use excessive.

There are two main methods of temperature control:

- <u>manual control</u>, in which the furnace operator adjusts burner firing rates in response to changes in stock throughput rates, sizes and qualities, and changes in the furnace temperature;
- <u>automatic or computer control</u>, in which the burners are adjusted in response to changes in temperature with minimal or no operator intervention.

8.3.1 *Thermocouples*

Thermocouples are most commonly used for temperature measurement and control. Thermocouples respond rapidly, are capable of operating over a wide temperature range with acceptable accuracy, and provide an easily readable electric output. A cold junction may be required to compensate for high ambient temperatures.

The most commonly used types of thermocouples are:

Type	Conductor Material			Temperature Range (°C)
R	Pt, 13%Rh	-	Pt	0 - 1,600
S	Pt, 10%Rh	-	Pt	0 - 1,550
B	Pt, 30%Rh	-	Pt, 6%Rh	100 - 1,600
K	NiCr	-	NiAl	0 - 1,100

(Pt, Rh, Ni, Cr and Al are the chemical symbols for platinum, rhodium, nickel, chromium and aluminium respectively).

It is normal practice to use a ceramic or metallic sheath; this protects the conductor materials from the furnace atmosphere and helps to maintain operating life and the calibrated condition. The speed of response may be reduced, but this is not generally sufficient to cause difficulties in furnace control.

Thermocouples are normally positioned through the roof of the furnace, or in some cases the sidewall, away from the direct influence of burners, flue ducts and doors. The depth of immersion should be approximately seven times the sheath diameter to ensure an adequate speed of response. Depending on size, a flanged support may be required.

8.3.2 *Radiation Pyrometers*

Alternatively, radiation pyrometers can be used for temperature measurement and control. Radiation pyrometers are becoming increasingly popular because they can read stock temperatures directly, and, in combination with computers, allow automatic control of the furnace. It should be noted that reflected radiation can interfere with the reading from this type of instrument. A 3.9 m pyrometer has been developed to overcome this problem, but temperature compensation using a thermocouple is still required. The system operates satisfactorily with gaseous fuels, but with oil the pyrometer needs to be carefully sited because the flame is more luminous than a gas flame (see Good Practice Guide 77, Section 6.4).

8.4 Computer Control

Computer control of continuous reheating furnaces provides a means of supervising zone temperatures and making automatic adjustments in response to changes in throughput rates and steel qualities. Computers allow consistent and rapid control, and remove variations induced by the manual intervention of furnace operatives. Computer control systems automatically take account of the operational strategies described in Section 11 that help to optimise furnace performance in response to production demands.

Although systems with different degrees of sophistication are available, the aim of all computer control systems is to produce satisfactory steel discharge temperatures with minimum energy use. This is achieved by avoiding over and under heating of the stock for all throughput conditions and steel qualities.

Fig 34 shows a basic computer control system. Furnace operating parameters monitored by the furnace instrumentation (e.g. thermocouples, optical pyrometers, pressure transducers, etc) form the input to the computer together with information pertaining to steel qualities and stock sizes. The computer uses the input data in an on-line mathematical model to predict stock temperatures and to calculate the desired furnace control settings for the optimum stock discharge condition. Control settings are adjusted either automatically or manually by the operator using the information displayed on the computer screen.

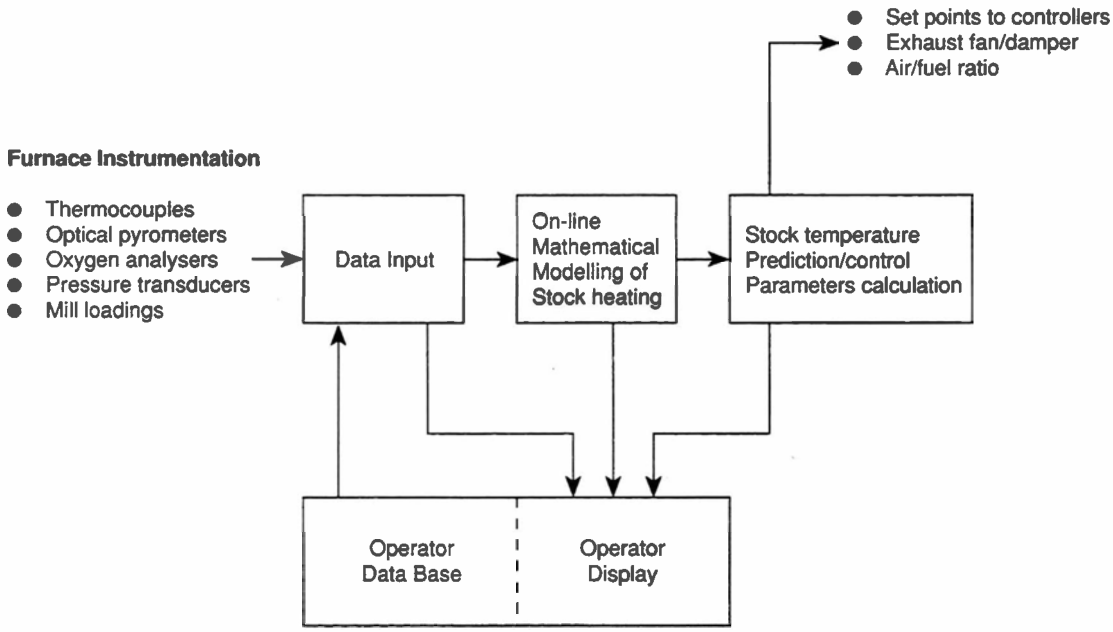


Fig 34 Computer control system schematic

Computer control allows unexpected production delays to be accommodated through set control procedures activated by the furnace instrumentation and mill sensors. Action on scheduled delays can be taken based on information concerning projected delay times and throughput rates entered into the computer by the furnace operatives.

9. MODELLING TECHNIQUES

Furnace design and operation can be simulated using mathematical and physical models. Modelling techniques are particularly useful for evaluating aspects that are difficult or impossible to investigate *in situ*.

The advantages of using modelling techniques include:

- a wide range of design options can be assessed without the need for prototype plant;
- technical and economic decision making are enhanced;
- visual demonstrations of technical detail and plant behaviour can be provided;
- information and data can be produced quickly, economically and safely;
- when modifications to existing furnaces are being considered, the use of modelling techniques can help to overcome practical difficulties in obtaining certain plant measurements and avoid disrupting production.

9.1 Mathematical Modelling

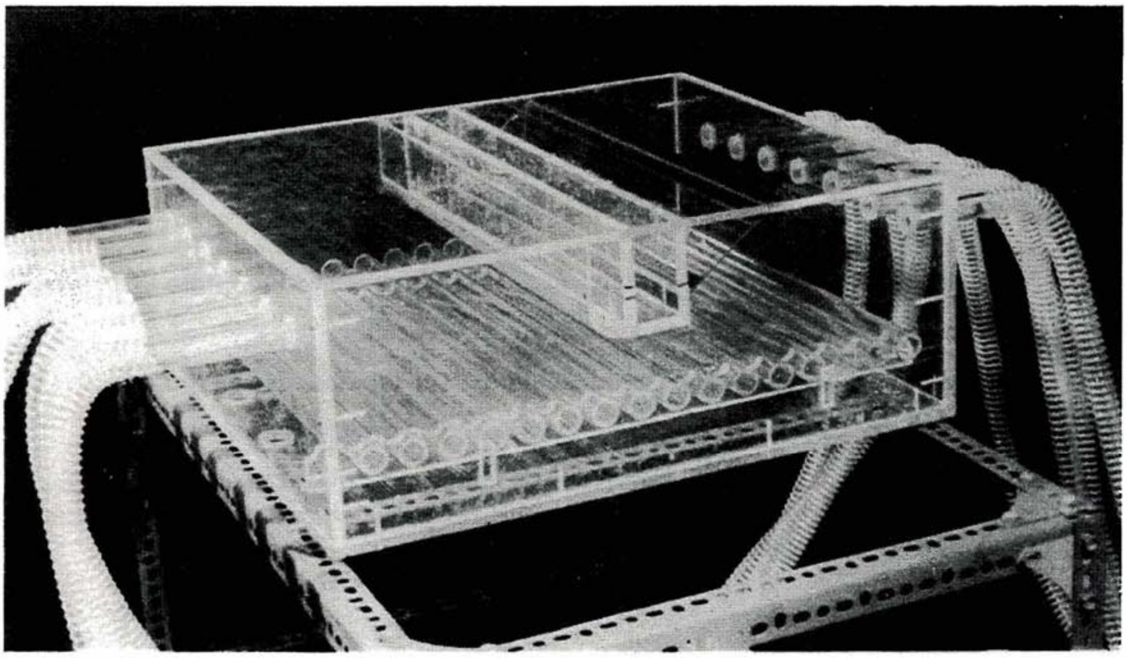
Mathematical modelling is used to investigate stock temperature heating rates, temperature uniformity and the thermal requirements (zoning and burner ratings) of a furnace. Complex numerical models that analyse fluid flow, gas mixing patterns, combustion characteristics and heat transfer rates are now available.

9.2 Physical Modelling

Physical modelling involves the construction of a small scale model of the furnace to provide information on flow patterns, rates of gas movement, mixing of gas streams, gas interactions between zones and pressure/flow characteristics. Although these aspects can sometimes be predicted from experience or empirical knowledge, physical modelling provides confirmation and the opportunity to gather qualitative and quantitative information. Such models are normally constructed in transparent plastic (to aid visualisation), but can be made of metal or wood if required. The design of a physical model uses well-established laws of scaling and similarity criteria; this may mean that the model is not a scaled replica of the full size furnace.

Cold air (isothermal modelling) or sometimes water is used to represent the flow of hot combustion gases; investigative techniques include the use of pitot static probes for measuring velocities and mass flow, and carbon dioxide tracer injection and sampling for studying gas mixing. Flow patterns can be visualised using smoke tracers, and in some circumstances balsa dust or expanded polystyrene balls. Dyes are used to visualise flow patterns in water models.

Fig 35 shows a typical example of the use of an isothermal physical model. The model was used to study the effect on flow patterns of various roof profiles in a walking beam furnace used to reheat steel tubes. Tests carried out on the model allowed flow patterns to be derived and an optimum roof shape to be designed. This enhanced the flow of hot gases in each zone, thus increasing productivity and improving the efficiency of fuel use.



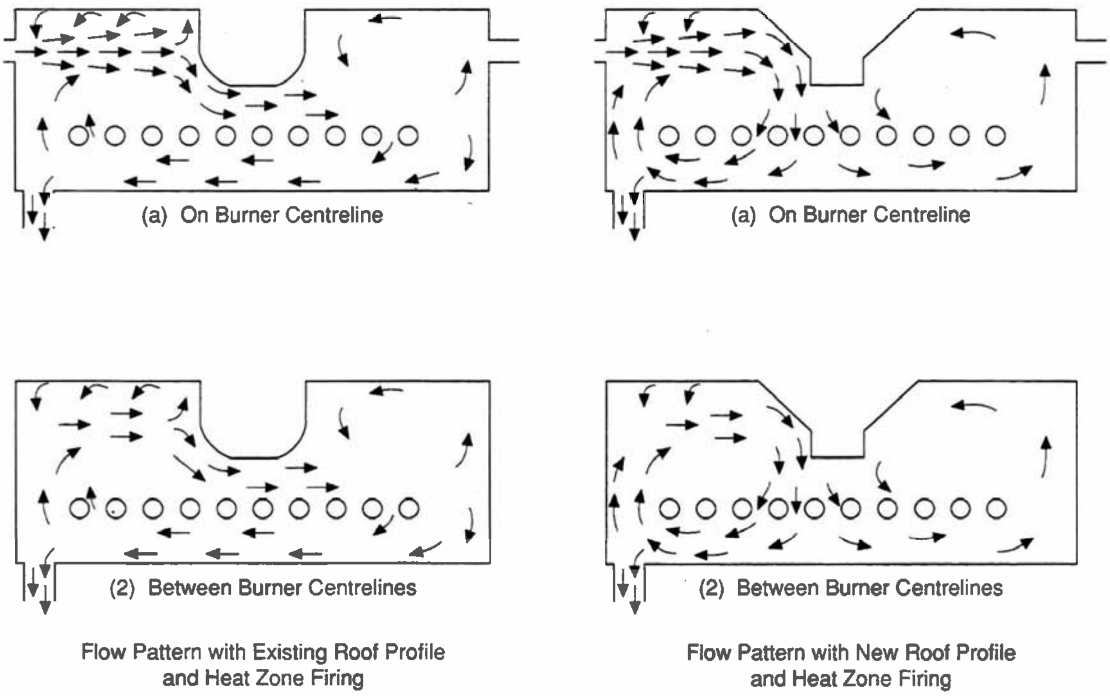


Fig 35 Physical model study of a continuous tube reheating furnace

10. EVALUATION OF DESIGN OPTIONS

There are no definitive rules or procedures that must be followed when optimising a design to meet a given furnace specification and objectives. Although the type of furnace and installed equipment will always depend on the individual circumstances, a hypothetical example is presented below. The example is a simplified case, which is presented to illustrate the effects of design. Furnace users are advised to seek expert advice at the design stage.

10.1 Hypothetical Example

10.1.1 *Furnace Specification*

The hypothetical furnace is required to reheat mild steel billets, 100 mm square and 10 m long, at a continuous rate of 100 tonne/hour to a minimum mean bulk temperature of 1,200°C. The maximum temperature difference within each billet should not exceed 25°C. The billets are to be charged cold, and the furnace will be in production for 120 hours each week and shut-down each weekend. Annual output will be 550,000 tonnes.

10.1.2 *Options for Reheating Furnaces*

The assumed maximum hourly output of 100 tonnes is taken to be the rolling mill's throughput capability; in practice the output may be less as production demands vary. Furnace design throughput ratings of less than the maximum are considered to illustrate the effects of furnace design rating on specific energy use.

Four different types of reheating facilities are possible:

Case 1	A top fired only pusher type furnace;
Case 2	A top.and bottom fired pusher type furnace;
Case 3	A top and bottom fired walking beam type furnace;
Case 4	A top fired only walking hearth type furnace.

It should be noted that the design options do not include rotary hearth type or continuous recirculating bogie type furnaces. These are precluded by the size and shape of the stock to be reheated.

It is assumed that the furnace will operate at a uniform temperature of 1,250°C, or that a temperature profile can be used with the furnace 'zoned' such that the temperature increases linearly from 850°C at the charge end to 1,250°C along one third of its length.

10.1.3 *Options for Waste Heat Recovery*

Three waste heat recovery systems are considered for each furnace design and temperature profile:

(a) Regenerative ceramic burners producing pre-heated combustion air at a temperature 200°C below the furnace exhaust gas temperature;

(b) Self-recuperative burners producing pre-heated combustion air temperatures of between 420°C and 470°C for the furnace operating temperatures considered;

(c) An external recuperator producing pre-heated combustion air temperatures of approximately 450°C.

The exhaust gas temperature is assumed to be 50°C above the furnace internal surface temperature at the point of extraction. The average exhaust gas temperature for a furnace fitted with regenerative or self-recuperative burners and operating with a temperature profile along its length is assumed to be 1,150°C.

The *furnace combustion efficiencies* for each furnace design and waste heat recovery system are shown in Table 7. These have been calculated on the basis of the heat content of the fuel and exhaust gases.

Table 7 Furnace combustion efficiency

Item	**Waste heat recovery system**					
	Regenerative burners		**Self-recuperative burners**		**Exhaust gas recuperator**	
Furnace temperature profile	1250°C along length	850°C at charge end	1250°C along length	850°C at charge end	1250°C along length	850°C at charge end
Exhaust temperature, °C	1300	1150	1300	1150	1300	900
Pre-heated combustion air temperature, °C	1100	950	470	420	450	450
Furnace combustion efficiency, %	72	73	46	52	46	66

Note: *Furnace combustion efficiency* based on an *excess combustion air* level of 15%

$$\text{Combustion efficiency} = \frac{\{\text{Heat in fuel} + \text{Heat in air} - \text{Heat in exhaust}\}}{\text{Heat in fuel}} \times 100\%$$

10.1.4 *Preparation of Energy Balances*

Energy balances have been prepared (see Section 3.5) which show the *specific energy consumption* levels for the four options. The following assumptions (which are approximately valid in practical situations) have been made:

1 The net heat absorbed by the steel (taking account of scale formation) is 0.8 GJ/tonne.

2 Structural energy losses from the furnace consist of:

(a) transmitted energy losses through the refractory structure;
(b) energy losses by radiation through doors and openings;
(c) water cooling energy losses.

These losses depend on the physical size of the furnace. A furnace with a variable temperature profile has a lower average shell temperature than one operating at a high temperature throughout, but it would also have a larger surface area because of its longer length. In this case, structural energy losses for unit area of the furnace have been assumed that are consistent with current practices and the same as for furnaces operating with uniform or profiled temperatures. Water cooling losses from walking hearth type and top fired only pusher type furnaces are assumed to be negligible.

3 Heat storages in the furnace refractories have been related to the unit area of the furnace and are typical values. These have been presented separately to distinguish between structural energy losses that occur during productive periods and weekend shut downs.

4 The fuel energy input is derived from the calculated total *heat release* within the furnace and the *combustion efficiencies* shown in Table 7.

The calculated structural energy losses from the furnace are shown in Table 8.

Table 8 Furnace structural energy losses

Component	Value
Productive energy losses	
Transmitted through structure, MJ/m^2	
Side walls	5.0
Roof	8.1
Hearth	2.3
End Walls	5.0
Radiation losses, MJ/h	900
Water cooling, MJ/h per metre length or furnace	1000
Energy losses during weekend shut down	
Stored in refractories MJ/m^2	
Side walls	880
Roof	640
Hearth	600
End Walls	880

The approximate furnace lengths shown in Table 9 are the minimum required for reheating cold charged billets of the specified size to the desired discharge condition. These furnace lengths have been derived from mathematical predictions of the thermal history of a billet in the furnace (see Fig 36), taking account of heat transferred to the individual billet faces for the furnace configurations considered. It has been assumed that there are no limits on the stock heating rates; in practice metallurgical constraints may be imposed, and these will have to be taken into account when establishing furnace operating temperatures, stock residence times and furnace length.

Table 9 Furnace length

Operation	Type of furnace							
	Case 1. Pusher (top fired only)		Case 2. Pusher (top and bottom fired)		Case 3. Walking beam (top and bottom fired)		Case 4. Walking hearth (top fired only)	
	1250°C along length	850°C at charge end	1250°C along length	850° at charge end	1250°C along length	850°C at charge end	1250°C along length	850°C at charge end
Billet residence time, min	100	114	40	44	24	28	54	62
Approximate furnace size, m								
Length	21.2	24.2	8.5	9.3	10.2	11.9	23.0	26.3
Width	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Height	2.0	2.0	4.0	4.0	4.0	4.0	2.0	2.0

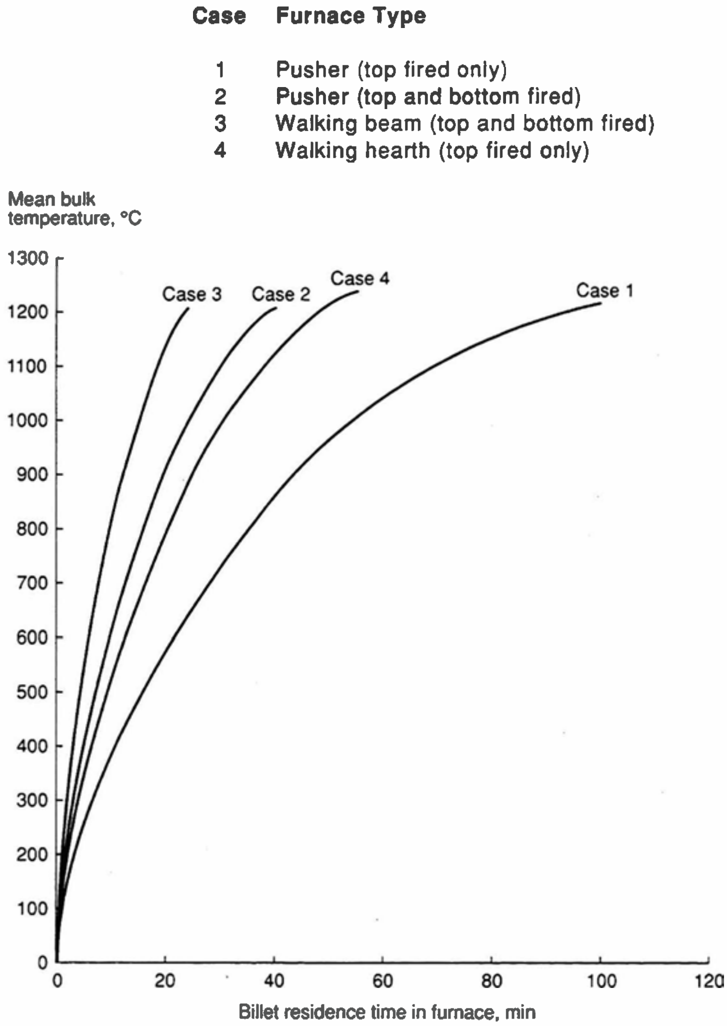


Fig 36 Predicted temperature of 100 mm square billet reheated in a furnace operating with a temperature of 1,250°C along its length

The calculated total *heat release* within the furnace for each design option is summarised in Table 10, while Fig 37 shows the effect of reduced productivity.

Table 10 Heat release within the furnace (based on 12,000 t/week (100 t/h) throughput)

Heat release within the furnace GJ/t	Type of furnace							
	Case 1. Pusher (top fired only)		Case 2. Pusher (top and bottom fired)		Case 3. Walking beam (top and bottom fired)		Case 4. Walking hearth (top fired only)	
	1250°C along length	850°C at charge end	1250°C along length	850° at charge end	1250°C along length	850°C at charge end	1250°C along length	850°C at charge end
Heat to steel (net	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Structural energy losses (transmitted)	0.03	0.04	0.02	0.02	0.02	0.02	0.03	0.04
Energy stored in refractories	0.04	0.04	0.02	0.02	0.03	0.03	0.04	0.04
Radiation loss	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Water cooling energy loss	0	0	0.08	0.09	0.10	0.12	0	0
Total heat release	0.88	0.89	0.93	0.94	0.96	0.98	0.88	0.89

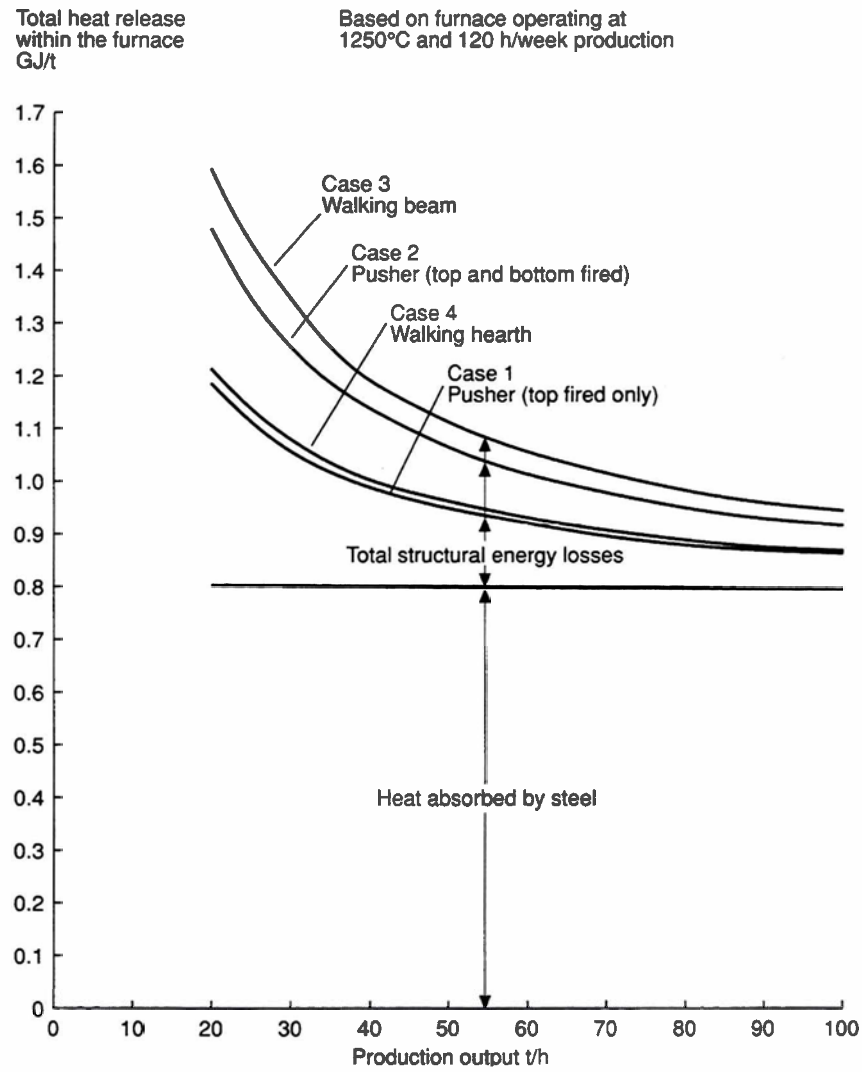


Fig 37 Total heat release within the furnace

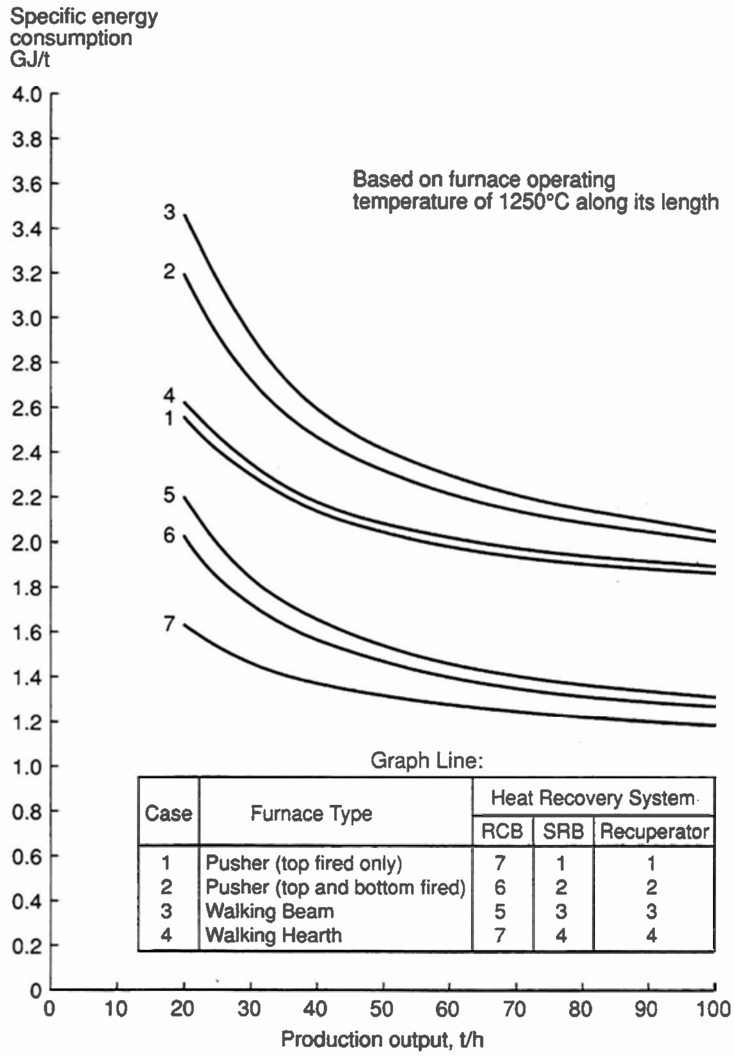
10.1.5 *Specific Energy Consumptions*

Specific energy consumptions (GJ/tonne) have been calculated from the energy balances, based on a 120 hour/week production at 100 tonnes/hour. *Specific energy consumption* has also been calculated for the same operating period, but with reduced output (see Fig 38). This demonstrates the effect of over design and reduced furnace availability on *specific energy consumption.*

10.1.6 *Discussion*

In each case, there are three main factors which significantly influence furnace energy use:

Water Cooling Energy Losses
The walking beam furnace has the highest cooling water energy losses and the walking hearth furnace the lowest. There are usually some water cooled elements e.g. lintels, door jambs, etc in top fired pusher furnaces, but energy losses from these can be assumed to be negligible. The cooling water losses in top and bottom fired pushers are normally lower than in walking beam type furnaces, because there are fewer cooled stock supporting members. In this example, however, the energy loss has been taken to be the same for both furnaces.



Case	Furnace Type	Heat Recovery System		
		RCB	SRB	Recuperator
1	Pusher (top fired only)	7	1	1
2	Pusher (top and bottom fired)	6	2	2
3	Walking Beam	5	3	3
4	Walking Hearth	7	4	4

Fig 38 Furnace specific energy consumption

For a walking beam furnace operating at a throughput of 100 tonne/hour (its design rating), cooling water losses account for 11% of the total heat release within the furnace. If the furnace operates at 50 tonne/hour (i.e. 50% of its design rating), the water cooling losses increase to 18% of the total. At 50 tonnes/hour and a furnace combustion efficiency of 46%, approximately 0.44 GJ of fuel per tonne of steel processed is lost in the cooling water. This demonstrates one disadvantage of using walking beam type furnaces. Such furnaces are more suited to situations requiring operational flexibility and uniform stock temperatures during heating. As these factors are not of primary importance in this example, the walking beam type furnace (Case 3) can be discounted on the grounds of its unacceptably high specific energy use.

2. <u>Waste Heat Recovery Method</u>

A furnace operating with a uniform temperature along its length has no capacity for *stock recuperation*, and *combustion efficiency* with regenerative burners is higher than that obtained with self-recuperative burners or an external recuperator. In contrast, operating with a temperature profile produces lower exhaust gas temperatures because of *stock recuperation*, giving similar *combustion efficiencies* for the regenerative and recuperator cases (see Table 7). For a furnace with either a profiled or uniform temperature, the use of self-recuperative burners would not be consistent with minimising energy use.

Furnace Design Rating

Specific energy consumption levels are sensitive to furnace design rating (tonne/hour) and availability. Careful consideration should therefore be given to matching furnace capability with future market demands and rolling mill capacity.

Site restrictions may limit the choice of new furnace design. A walking beam furnace, which is approximately half the length of a top fired pusher of equivalent rating, is advantageous in this respect, but is also the most energy intensive. Assuming that space is not a limitation, then a walking hearth furnace (Case 4) operated with a temperature profile along its length and fired by regenerative burners or fitted with a suitable external recuperator for waste heat recovery appears to be the best option in terms of specific energy use. It satisfies the requirements of this hypothetical case and has the advantages of a low specific energy use and flexibility of operation compared with the other options.

PART C: ACTION PLAN

This part of the Guide provides an action plan for specification, design and equipment aspects of continuous furnaces. Good Practice Guide 77 provides a similar plan when considering operational aspects.

A number of agencies and organisations offer advice on all aspects of furnace design and operation. These include furnace builders, energy consultants, and equipment and materials suppliers. For major improvements such organisations are probably best placed to offer advice and help.

For most furnace users, there is usually sufficient technical competence 'in-house' to allow many inexpensive steps to be taken that achieve significant energy savings. As a first step, an overall energy balance for the furnace should be prepared. This requires wall (structural) temperatures and steel discharge temperatures to be measured, and some knowledge of typical waste gas conditions. The energy balance will highlight areas where energy is being wasted and give some indication of the potential for improvement. Help should be sought from appropriate organisations for those measurements which require special equipment or expertise.

The following sections summarise the major considerations in optimising furnace energy use that need to be addressed at the furnace design stage, or if it is to be modified or refurbished. Furnace users should be wary of attempting their own design, and it is essential to collaborate closely with specialist builders to ensure that the final design fully meets the requirements and objectives.

11. DESIGN CONSIDERATIONS

11.1 Requirements

When considering furnace design, the most important requirements which must be taken into account are:

1 Furnace Specification

- Range of stock shapes and sizes
- Charge and discharge temperatures
- Stock temperature uniformity at discharge
- Stock temperature uniformity during heating
- Stock heating rate
- Productivity

2 Objectives

- Flexibility of operation
- Energy use and costs
- Product quality

3 Other Parameters

- Maintenance
- Reliability
- Accessibility
- Weekend shut-down
- Down-shifts
- Compatibility with existing plant

11.2 Options

The options to be considered for a furnace design are:

1 Transport Mechanism
- Pusher, walking beam, walking hearth or others
- Charge and discharge facilities

2 Furnace Geometry
- Nominal dimensions (length, width, height)
- Burner positions

3 Zoning of Burners

4 Firing Arrangements
- Longitudinal, sidewall, roof
- Cold/hot air
- Low/medium/high velocity burners
- Self-recuperative/regenerative burners

5 Waste Heat Recovery
- Recuperators, regenerative burners, self-recuperative burners
- Stock recuperation

6 Other Energy Related Aspects
- Evaporative cooling
- Low thermal mass insulation
- Door openings/locations

7 Other Considerations
- Mathematical modelling
- Physical modelling

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APPENDIX 1

GLOSSARY OF TERMS

Burner Quarls	refractory components surrounding the burner nozzle.
Calorific Value (CV)	the heat liberated by the complete combustion of a unit quantity of fuel. The gross calorific value is the total heat available after the water formed as a combustion product has condensed. The net calorific value signifies that the water formed is still a vapour.
Cobbles	occur when steel being rolled in the mill becomes entangled in the mill rolls or misses the gap between the rolls and buckles and/or deforms.
Down-shift	a period, usually more than a manned shift, when there is no production and the furnace is maintained at a lower temperature than normal.
Excess Combustion Air or Excess Air	the air, above the stoichiometric requirement, which is supplied to assist the combustion of a fuel.
Flammability Limits	a fuel will not burn if there is too little or too much oxygen in the air/fuel mixture. There is therefore an upper (or fuel lean) limit and a lower (or fuel rich) limit between which combustion can be sustained.
Furnace Combustion Efficiency - or Combustion Efficiency	the proportion of the energy in the fuel (based on its calorific value) used to satisfy all the heating requirements and energy losses associated with the furnace excluding the heat content of the exhaust gases. It is usually expressed as a percentage.
Furnace Efficiency	the amount of energy transferred to the stock in the furnace (excluding the energy released due to the formation of scale). It is expressed as a percentage of the fuel energy supplied to the furnace.
Heat Release	the proportion of fuel energy supplied to the furnace that does not leave the furnace in the exhaust gases. It is the sum of all the energies put into the stock, furnace structure, etc and the energy losses that occur within the furnace that are necessary to satisfy process requirements.
Ignition Temperature	the temperature at which the mixture of fuel gas or vapour and air or oxygen will maintain combustion.
Latent Heat	the heat required to change the state of a unit mass of a substance from one phase to another without change of temperature. It has units of joules/kg (J/kg). The specific latent heat of fusion is the heat required to convert 1 kg of solid at its melting point into a liquid at the same temperature. The specific latent heat of vaporisation is the heat required to convert 1 kg of liquid at its boiling point into a vapour at the same temperature.
Light-up	the period when the furnace temperature is being raised in preparation for production e.g. following a period when the burners have been turned off.

Monolithic Refractories	a refractory which is formed in place, and is not made of preformed bricks or profiles.
Nozzle Mix Burners	a class of burner in which combustion take place in a refractory tunnel or quarl beyond the combustion air and fuel inlets.
Oxygen Enrichment	the practice of adding oxygen to combustion air to increase its oxygen content. Typically between the normal atmospheric ratio (21%) and 26%.
Premix Burners	a class of burner in which the combustion air and fuel are mixed to varying degrees before they leave the burner.
Sankey Diagram	a graphical representation of the energy supplied to and taken out of a system. The inputs and outputs are represented by streams whose widths are proportional to the amount of energy.
Sensible Heat	the heat absorbed or released by a substance moving between two temperatures without changing its physical state.
Stoichiometric	the exact proportions in which substances react. For combustion, the theoretical minimum amount of air or oxygen required to completely consume the fuel.
Sub-Stoichiometric	when there is insufficient air or oxygen to allow complete combustion of the fuel.
Skids	horizontal longitudinal beams or rails in reheating furnaces that support the stock. Skids can be water cooled and, in top and bottom fired furnaces, supported by an arrangement of vertical and crosswise beams.
Soak Zone	- the final zone before discharge where the stock reaches its final processing temperature uniformly.
Specific Energy Consumption	- the amount of energy used to reheat a unit weight (usually one tonne) of steel.
Stock Recuperation	- a technique whereby the exhaust gases leave the furnace at the charge end, thus enabling their waste energy to preheat the stock.
Thermal Conductivity	the physical property of a material that describes the rate of flow of heat through a unit surface area of a material. The SI unit is watts per metre Kelvin ($W\ m^{-1}\ K^{-1}$).
Thermal Spalling	the splintering or breaking up of the surface of refractory bricks caused by subjecting the surface to excessive or rapidly changing temperatures.
Tonnage Zone	the main heating zone, where the most rapid rise in stock temperature takes place.
Turn-down Ratio	the ratio between the heat output of a burner on its highest and lowest settings.